CHAPTER 4

SLOW RATE PROCESS DESIGN

4.1 Introduction

The key elements in the design of slow rate (SR) systems are indicated in Figure 4-1. Important features are: (1) the iterative nature of the procedure, and (2) the input information that must be obtained for detailed design.

Determining the design hydraulic loading rate is the most important step in process design because this parameter is used to determine the land area required for the SR system. The design hydraulic loading rate is controlled by either soil permeability or nitrogen limits for typical municipal wastewater. Crop selection is usually the first design step because preapplication treatment, hydraulic and nitrogen loading rates, and storage depend to some extent on the crop. Preapplication treatment selection usually precedes determination of hydraulic loading rate because it can affect the wastewater nitrogen concentration and, therefore, the nitrogen loading.

4.2 Process Performance

The mechanisms responsible for treatment and removal of wastewater constituents such as BOD, suspended solids (SS), nitrogen, phosphorus, trace elements, microorganisms, and trace organics are discussed briefly. Levels of removal achieved at various SR sites are included to show how removals are affected by loading rates, crop, and soil characteristics. Chapter 9 contains discussion on the health and environmental effects of these constituents.

4.2.1 BOD and Suspended Solids Removal

BOD and SS are removed by filtration and bacterial action as the applied wastewater percolates through the soil. BOD and SS are normally reduced to concentrations of less than 2 mg/L and less than 1 mg/L, respectively, following 1.5 m (5 ft) of percolation. Typical loading rates of BOD and SS for municipal wastewater SR systems, regardless of the degree of preapplication treatment, are far below the loading rates at which performance is affected (see Section 2.2.1.1). <u>Thus, loading rates for BOD and SS are normally not a concern in the design of SR systems</u>. Removals of BOD achieved at five selected sites are presented in Table 4-1.

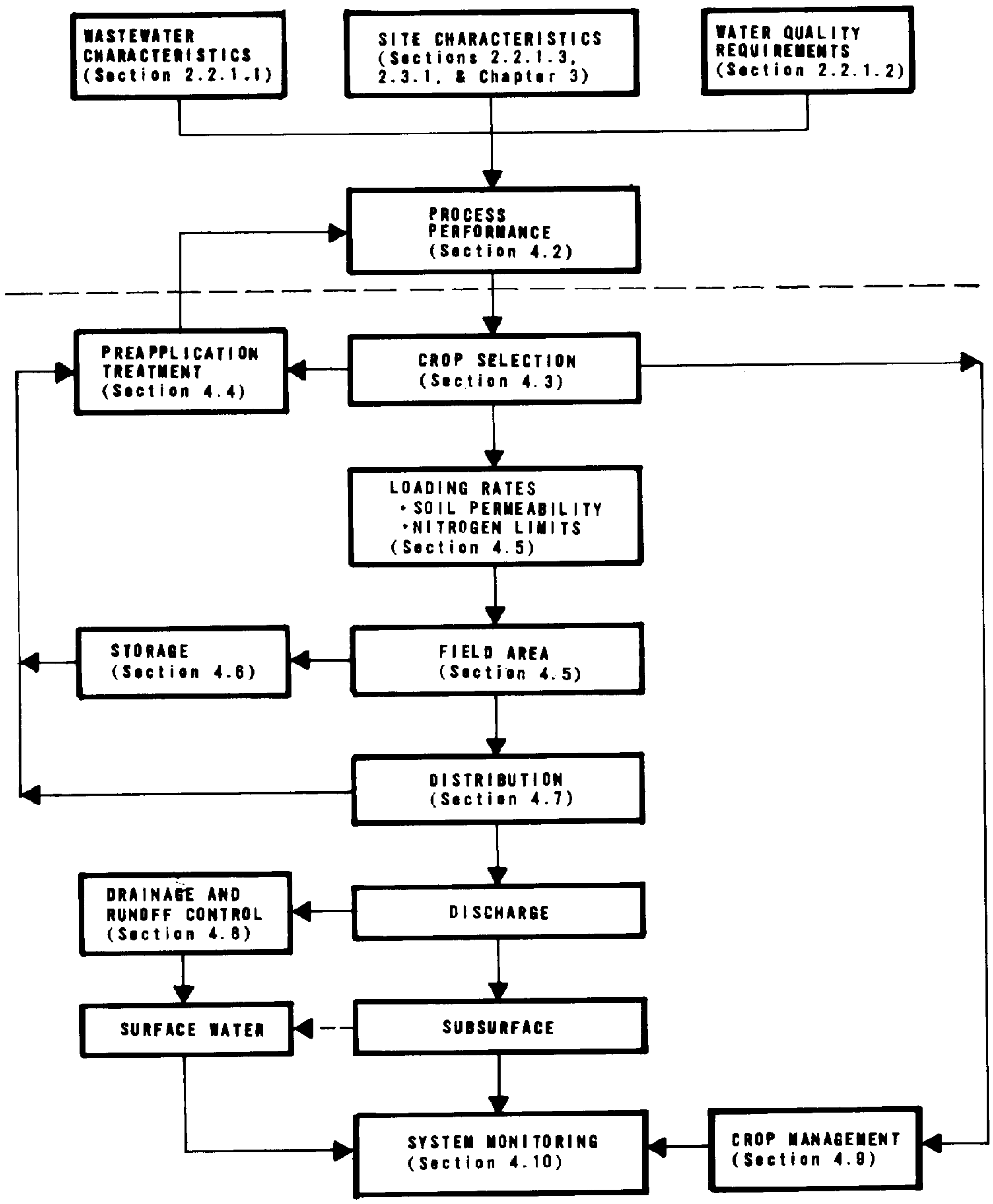


FIGURE 4-1
SLOW RATE DESIGN PROCEDURE

TABLE 4-1
BOD REMOVAL DATA
FOR SELECTED SR SYSTEMS [1-5]

Location	Annual waste-water loading rate, cm/yr	Surface soil	BOD			
			Concentration in applied wastewater, mg/L	Concentration in treated water, mg/L	Removal, %	Sampling depth, m
Dickinson, North Dakota	140	Sandy loams and loamy sands	42	<1	>98	<5
Hanover, New Hampshire	130-780	Sandy loam and silt loam	40-92	0.9-1.7	96-98	1.5
Muskegon, Michigan	130-260	Sands and loamy sands	24	1.3	94	4
Roswell, New Mexico	80	Silty clay loams	42	<1	>98	<30
San Angelo, Texas	290	Clay and clay loam	89	0.7	99	2.1

Note: See Appendix G for metric conversions.

4.2.2 Nitrogen

For SR systems located above potable aquifers, nitrogen concentration in percolate must be low enough that ground water quality at the project boundary can meet drinking water nitrate standards. Nitrogen removal mechanisms at SR systems include crop uptake, nitrification-denitrification, ammonia volatilization, and storage in the soil. Percolate nitrogen concentrations less than 10 mg/L can be achieved with SR systems if the nitrogen loading rate is maintained within the combined removal rates of these mechanisms. The nitrogen removal rates and loading rate are, therefore, important design parameters. Percolate nitrogen levels achieved at selected SR sites are given in Table 4-2.

Crop uptake is normally the primary nitrogen removal mechanism operating in SR systems. The amount of nitrogen removed by crop harvest depends on the nitrogen content of the crop and the crop yield. Annual nitrogen uptake rates for specific crops are given in Section 4.3.2.1. Maximum nitrogen removal can be achieved by selecting crops or crop combinations with the highest nitrogen uptake potential.

TABLE 4-2
NITROGEN REMOVAL DATA FOR SELECTED
SR SYSTEMS [1, 3-8]

Location	Total nitrogen concentration in applied wastewater, mg/L as N	Total nitrogen concentration in percolate or affected ground water, mg/L as N	Removal, %	Sampling depth, m	Total nitrogen concentration in background ground water, mg/L as N
Dickinson, North Dakota	11.8	3.9	67	11	1.9
Hanover, New Hampshire	27-28	7.3	72	1.5	--
Helen, Georgia[a]	18.0	3.5	80	1.2	0.17
Roswell, New Mexico	66.2	10.7	84	30	2.2
San Angelo, Texas	35.4	6.1	83	10	--

a. Forest system. All others are agricultural systems.

Nitrogen loss by denitrification depends on several environmental factors including the oxygen level in the soil. Assuming that most of the applied nitrogen is in the organic or ammonium form, increased nitrogen removal due to denitrification can be expected under the following conditions:

! High levels of organic matter in the soil and/or wastewater, such as the concentrations found in primary effluent

! High soil cation exchange capacity--a characteristic of fine-textured and organic soils.

! Neutral to slightly alkaline soil pH

! Alternating saturated and unsaturated soil moisture conditions

! Warm temperatures

Denitrification losses typically are in the range of 15 to 25% of the applied nitrogen, although measured losses have ranged from 3 to 70% [4, 9]. <u>The range of 15 to 25% should be used for conservative design</u>. When conditions are favorable, the maximum rate may be used. Lower values should be used when conditions are less favorable.

Ammonia volatilization losses can be significant (about 10%) if the soil pH is above 7.8 and the cation exchange capacity is low (sandy, low organic soils). For design, volatilization losses may be considered included in the 15 to 25% used for denitrification.

Storage of nitrogen in the soil through plant uptake and subsequent conversion of roots and unharvested residues into soil humus can account for nitrogen retention rates up to 225 kg/ha•yr (200 lb/acre•yr) in soils of arid regions initially low in organic matter (less than 2%). In contrast, nitrogen storage will be near zero for soils rich in organic matter. In either case, if nitrogen input remains constant, the rate of nitrogen storage will decrease with time because the rate of decay and release of nitrogen increases with the concentration of soil organic nitrogen. Eventually, an equilibrium level of organic nitrogen may be obtained and net storage then ceases. Therefore, for design purposes, the most conservative approach is to assume net storage will be zero.

4.2.3 Phosphorus

Phosphorus is removed primarily by adsorption and precipitation (together referred to as sorption) reactions in the soil. Crop uptake can account for phosphorus removals in the range of 20 to 60 kg/ha-yr (18 to 53 lb/acre yr), depending on the crop and yield (Section 4.3.2.1). Percolate phosphorus concentrations at several SR sites are presented in Table 4—3.

The phosphorus sorption capacity of a soil profile depends on the amounts of clay, aluminum, iron, and calcium compounds present and the soil pH. In general, fine textured mineral soils have the highest phosphorus sorption capacities and coarse textured acidic or organic soils have the lowest.

For systems with coarse textured soils and limits on the concentration of percolate phosphorus, a phosphorus adsorption test should be conducted using soil from the selected site. This test, described in Section 3.7.2, determines the amount of phosphorus that the soil can remove during short application periods. Actual phosphorus retention at an operating system will be at least 2 to 5 times the value obtained during a 5 day adsorption test [13].

TABLE 4-3
PHOSPHORUS REMOVAL DATA FOR TYPICAL
SR SYSTEMS [1,2,4,5,7,8,10-12]

Location	Annual wastewater loading rate, cm/yr	Surface soil	PO_4 concentration in applied wastewater, mg/L as P	Soluble PO_4 concentration in affected ground water, mg/L as P	Removal, %	Sampling depth, m	Distance from application site, m	Soluble PO_4 concentration in background ground water, mg/L as P
Agricultural systems								
Camarillo, California	160	Clay loams and sandy loams	11.8[a] 11.8[a]	2.8[a] 0.2[a]	76[a] 98[a]	1 3	0 0	3.0[a] --
Dickinson, North Dakota	140	Sandy loams and loamy sands	6.9[a]	0.05[a]	99[a]	<5	30-150	0.04[a]
Hanover, New Hampshire	130-78	Sandy loam and silt loam	7.3-7.6[a]	0.03-0.07[b]	99.0-99.5	1.5	0	--
Mesa, Arizona	400-860	Loamy sands and sandy loams	9.0[b] 9.0[b]	5.0[b] 4.2[b]	44[b] 53[b]	0.5 1	0 0	1.0[b] 3.6[b]
Muskegon, Michigan	130-260	Sands and loamy sands	1.0-1.3[a]	0.03-0.05[a]	95-98[a]	1.5	0	0.03[a]
Roswell, New Mexico	80	Silty clay loams	7.95[a]	0.39[a]	95[a]	<6	0	0.55[a]
Tallahassee, Florida		Sand						
Winter	520		10.5[a]	0.1[a]	>99[a]	1.2	0	0.02[a]
Summer	1,040		10.5[a]	0.0[a]	>99[a]	10.7	0	0.02[a]
Forest systems								
Helen, Georgia	380	Sandy loam	13.1[a]	0.22[a]	98[a]	1.2	0	0.21[a]
State College, Pennsylvania (Penn State University)	260	Sandy loams and clay loams	7.7[b]	0.08[b]	99[b]	1.2	0	0.03[b]

a. Total phosphate concentration.

b. Orthophosphate concentration.

For purposes of design and operation, the soil profile can be considered to have a finite phosphorus sorption capacity associated with each layer. Eventually, the sorption capacity of the entire soil profile may reach saturation and soluble phosphorus will appear in the percolate. In cases where effluent quality requirements limit the concentration of phosphorus in the percolate, the useful life of the SR system may be limited by the phosphorus sorption capacity of the soil profile. An empirical model to predict the useful life of an SR system has been developed [9].

4.2.4 Trace Elements

Trace element removal in the soil is a complex process involving the mechanisms of adsorption, precipitation, ion exchange, and complexation. Because adsorption of most trace elements occurs on the surfaces of clay minerals, metal oxides, and organic matter, fine textured and organic soils have a greater adsorption capacity for trace elements than sandy soils.

Removal of trace elements from solution is nearly complete in soils suitable for SR systems. <u>Consequently, trace element removal is not a concern in the design procedure</u>. Performance data from selected SR systems are presented in Table 4-4.

Although some trace elements can be toxic to plants and consumers of plants, no universally accepted toxic threshold values for trace element concentrations in the soil or for mass additions to the soil have been established. Maximum loadings over the life of a system for several trace elements have been suggested for soils having low trace element retention capacities and are presented in Table 4-5.

Toxicity hazards can be minimized by maintaining the soil pH above 6.5. Most trace elements are retained as unavailable insoluble compounds above pH 6.5. Methods for adjusting soil pH are discussed in Section 4.9.1.3.

4.2.5 Microorganisms

Removal of microorganisms, including bacteria, viruses, and parasitic protozoa and helminths (worms), is accomplished by filtration, adsorption, desiccation, radiation, predation, and exposure to other adverse conditions. Because of their large size, protozoa and helminths are removed primarily by filtration at the soil surface. Bacteria also are removed by filtration at the soil surface, although adsorption may be important. Viruses are removed almost entirely by adsorption.

TABLE 4-4
TRACE ELEMENT BEHAVIOR DURING
SR LAND TREATMENT [14]

Element	EPA drinking water standard, mg/L	Raw municipal wastewater concentration, mg/L	Muskegon, Michigan[a]		San Angelo, Texas[b]		Melbourne, Australia[c]	
			Percolate concentration, mg/L	Removal, %	Percolate concentration, mg/L	Removal, %	Percolate concentration, mg/L	Removal, %
Cadmium	0.01	0.004-0.14	<0.002	90	<0.004	--[d]	0.002	80
Chromium	0.05	0.02-0.7	0.004	90	<0.005	>98	0.03	90
Copper	1.0	0.02-3.4	0.002	90	0.014	85	0.02	95
Lead	0.05	0.05-1.3	<0.050	>40	<0.050	--[d]	0.01	95
Manganese	0.05	0.11-0.14	0.26	15	--	--	--	--
Mercury	0.002	0.002-0.05	<0.002	--[d]	--	--	0.0004	85
Zinc	5.0	0.03-83	0.033	95	0.102	25	0.04	95

a. Data represent average annual concentrations (1975) found in underdrains placed at a depth of 1.5 m below the irrigation site.

b. Data represent average annual concentrations (November 1975 - November 1976) found in two seepage creeks adjacent to the irrigated area.

c. Data represent average annual concentrations (1977) found in underdrains placed at depths of 1.2 to 1.8 m below the irrigation site.

d. Percent removal was not calculated since influent and percolate values are below lower detection limit.

TABLE 4-5
SUGGESTED MAXIMUM APPLICATIONS OF TRACE ELEMENTS TO SOILS WITHOUT FURTHER INVESTIGATION[a]

Element	Mass application to soil, kg/ha	Typical concentration, mg/L[b]
Aluminum	4,570	10
Arsenic	92	0.2
Berylium	92	0.2
Boron	680	1.4[c]
Cadmium	9	0.02
Chromium	92	0.2
Cobalt	46	0.1
Copper	184	0.4
Fluoride	920	1.8
Iron	4,570	10
Lead	4,570	10
Lithium	--	2.5[d]
Manganese	184	0.4
Molybdenum	9	0.02
Nickel	184	0.4
Selenium	18	0.04
Zinc	1,840	4

a. Values were based on the tolerances of sensitive crops, mostly fruits and vegetables, grown on soils with low capacities for retaining elements in unavailable forms [15, 16].

b. Based on reaching maximum mass application in 20 years at an annual application rate of 2.4 m/yr (8 ft/yr).

c. Boron exhibits toxicity to sensitive plants at values of 0.75 to 1.0 mg/L.

d. Lithium toxicity limit is suggested at 2.5 mg/L concentration for all crops, except citrus which uses a 0.075 mg/L limit. Soil retention is extremely limited.

As noted in Table 1-3, fecal coliforms are normally absent after wastewater percolates through 1.5 m (5 ft) of soil. Coliform removals at several operating SR systems are shown in Table 4-6. Coliform removal in the soil profile is approximately the same when primary or secondary preapplication treatment is provided [4]. Virus removals are not as well documented. State agencies may require secondary treatment if edible crops are grown or if public contact is unlimited. <u>Microorganism removal is not a limiting factor in the SR design procedure</u>.

TABLE 4-6
COLIFORM DATA FOR SEVERAL
SR SYSTEMS [1,4,5,8,12]

Location	Preapplication treatment	Coliforms	Concentration in applied wastewater, MPN/100 mL	Concentration in percolate or ground water, MPN/100 mL	Distance of travel, m	Concentration in background ground water, MPN/100 mL
Camarillo, California	Activated sludge and disinfection	Total	57×10^3	7 29	0.5 1.0	4 27
		Fecal	220	<2 <2	0.5 1.0	<2 4
Dickinson, North Dakota	Aerated ponds and disin-fection	Total Fecal	TNTC[a] TNTC[a]	12 0	30-150 30-150	1 0
Hanover, New Hampshire	Primary	Fecal	1.2×10^4- 3.1×10^5	0-1	1.5	--
Mesa, Arizona	Trickling filters	Total	3.09×10^6	<2 9	0.5 1.0	20 60
		Fecal	1.05×10^5	<2 9	0.5 1.0	<2 25
Roswell, New Mexico	Trickling filters and disinfection	Total Fecal	TNTC[a] TNTC[a]	TNTC[a] 52	<6 <6	-- --

a. At least one sample too numerous to count.

4.2.6 Trace Organics

Trace organics are removed by several mechanisms, including sorption, degradation, and volatilization. One study at Muskegon, Michigan, evaluated the effectiveness of trace organics removal during preapplication treatment (aerated ponds) and SR treatment. Although 59 organic pollutants were identified in the raw wastewater, renovated water from drainage tiles underlying the irrigation site contained only low levels of 10 organic compounds, including two from non-wastewater sources. Benzene, chloroform, and trichloroethylene were monitored for several days; results are shown in Table 4-7.

Results from pilot SR studies at Hanover, New Hampshire, indicate that significant levels of volatile trace organics are removed during sprinkler application [4]. Measurements of chloroform, toluene, methylene chloride, 1,1 dichloroethane, bromodichloromethane, and tetrachloroethylene showed that an average of 65% of these six compounds were volatilized during the sprinkling process, with individual removals ranging from 57% for toluene to 70% for methylene chloride.

TABLE 4-7
BENZENE, CHLOROFORM, AND TRICHLOROETHYLENE
IN MUSKEGON WASTEWATER TREATMENT SYSTEM [17]

Pollutant	Sampling point[b]	Concentration, μg/L[a]				
		8/10/76	8/11/76	8/12/76	9/7/76	9/8/76
Benzene	1	6	53	6	41	32
	2	7	2	<1	8	5
	3	<1	<1	<1	3	2
	4	<1	<1	<1	<1	8
Chloroform	1	425	440	480	360	2,645
	2	105	61	81	365	610
	3	12	9	4	100	75
	4	3	3	1	13	10
Trichloroethylene	1	13	6	10	110	120
	2	16	3	5	35	33
	3	7	4	1	11	6
	4	6	3	2	10	8

a. Average for duplicate samples.

b. Sampling Point 1 - influent
Sampling Point 2 - aerated lagoon effluent
Sampling Point 3 - storage lagoon effluent
Sampling Point 4 - renovated water from drainage tiles

Based on these results, it appears that a typical SR system is quite effective in removing trace organics. However, if a community*s wastewater contains large concentrations of trace organics from industrial contributions, industrial pretreatment should be considered. If hazardous chlorinated trace organics result from wastewater chlorination, the engineer must decide in consultation with regulatory authorities whether it is more important to remove pathogens or to reduce trace organic levels. This decision should take into consideration the type of crop and the method of distribution.

4.3 Crop Selection

The crop is a critical component in the SR process. It removes nutrients, reduces erosion, maintains or increases infiltration rates, and can produce revenue where markets exist.

4.3.1 Guidelines for Crop Selection

Important characteristics or properties of crops that should be considered when selecting a crop for SR systems include: (1) nutrient uptake capacity, (2) tolerance to high soil moisture conditions, (3) consumptive use of water and irrigation requirements, and (4) revenue potential. A relative comparison of these characteristics for several types of crops is presented in Table 4-8 as a general guide to selection. Characteristics of secondary importance include (1) effect on soil infiltration rate, (2) crop water quality requirements and toxicity concerns, and (3) management requirements.

Most SR systems are designed to minimize land area by using maximum hydraulic loading rates. Crops that are compatible with high hydraulic loading rates are those having high nitrogen uptake capacity, high consumptive water use, and high tolerance to moist soil conditions. Other desirable crop characteristics for this situation are low sensitivity to wastewater constituents, and minimum management requirements. Crops grown for revenue must have a ready local market and be compatible with wastewater treatment objectives.

4.3.1.1 Agricultural Crops

Agricultural crops most compatible with the objective of maximum hydraulic loading are the forage and turf grasses. Forage crops that have been used successfully include: Reed canarygrass, tall fescue, perennial ryegrass, Italian ryegrass, orchardgrass, and bermudagrass. If forage utilization and value are not a consideration, Reed canarygrass is often a first choice in its area of adaptation because of high nitrogen uptake rate, winter hardiness, and persistence. However, Reed canarygrass is slow to establish and should be planted initially with a companion grass (ryegrass, orchardgrass, or tall fescue) to provide good initial cover.

Of the perennial grasses grown for forage utilization and revenue under high wastewater loading rates, orchardgrass is generally considered to be more acceptable as animal feed than tall fescue or Reed canarygrass. However, orchardgrass is prone to leaf diseases in the southern and eastern states. Tall fescue is generally preferred as a feed over Reed canarygrass but is not suitable for use in the northern tier of states due to lack of winter–hardiness. Again, other crops may be more suitable for local conditions and advice of local farm advisers or extension specialists will be helpful in making the crop selection.

Corn will grow satisfactorily where the water table depth is about 1.5 to 2 m, (5 to 7 ft) but alfalfa requires naturally well-drained soils and water table depths of at least 3 m (10 ft) for persistence. The alfalfa cultivar selected should be high yielding with resistance to root rot and bacterial wilt in the growing region, especially when high hydraulic loading rates (>7.5 cm/wk or 3 in./wk) are used.

TABLE 4-8
RELATIVE COMPARISON OF CROP CHARACTERISTICS [Adapted from 18]

	Potential as revenue producer[a]	Potential as water user[b]	Potential as nitrogen user[c]	Moisture tolerance[d]
<u>Field crops</u>				
Barley	Marg	Mod	Marg	Low
Corn, grain	Exc	Mod	Good	Mod
Corn, silage	Exc	Mod	Exc	Mod
Cotton (lint)	Good	Mod	Marg	Low
Grain, sorghum	Good	Low	Marg	Mod
Oats	Marg	Mod	Poor	Low
Rice	Exc	High	Poor	High
Safflower	Exc	Mod	Exc	Mod
Soybeans	Good	Mod	Good-exc[e]	Mod
Wheat	Good	Mod	Good	Low
<u>Forage crops</u>				
Kentucky bluegrass	Good	High	Exc	Mod
Reed canarygrass	Poor	High	Exc	High
Alfalfa	Exc	High	Good-exc[e]	Low
Bromegrass	Poor	High	Good	High
Clover	Exc	High	Good-exc[e]	Mod-high
Orchardgrass	Good	High	Good-exc[e]	Mod
Sorghum—sudan	Good	High	Exc	Mod
Timothy	Marg	High	Good	High
Vetch	Marg	High	Exc	High
Tall fescue	Good	High	Good-exc	High
<u>Turf crops</u>				
Bentgrass	Exc	High	Exc	High
Bermudagrass	Good	High	Exc	High
<u>Forest crops</u>				
Hardwoods	Exc	High	Good-exc[f]	High[g]
Pine	Exc	High	Good[f]	Mod-low[g]
Douglas-fir	Exc	High	Good[f]	Mod

a. Potential as revenue producers is a judgmental estimate based on nationwide demand. Local market differences may be substantial enough to change a marginal revenue producer to a good or excellent revenue producer and vice versa. Some of the forages are extremely difficult to market due to their coarse nature and poor feed values.

b. Water user definitions expressed as a fraction of alfalfa consumptive-use.

High	0.8-1.0
Moderate (Mod)	0.6-0.79
Low	-≤0.6

c. Nitrogen user ratings (kg/ha)

Excellent (Exc)	≥200
Good	150-200
Marginal (Marg)	100-150
Poor	≤100

d. Moisture tolerance ratings:
- High - withstands prolonged soil saturation >3 days.
- Moderate - withstands soil saturation 2-3 days.
- Low - withstands no soil saturation.

e. Legumes will also take nitrogen from the atmosphere.

f. Higher nitrogen uptake during juvenile growth stage after crowning.

g. Species dependent, check with the State Extension Forester.

A mixture of alfalfa and a persistent forage grass, such as orchardgrass, can be used on soils that are not naturally well drained. At high hydraulic loading rates, the alfalfa may not persist over 2 years, but the forage grass will fill in the areas in the thinned alfalfa stand.

The most common agricultural crops grown for revenue using wastewater are corn (silage), alfalfa (silage, hay, or pasture), forage grass (silage, hay, or pasture), grain sorghum, cotton, and grains [18]. However, any crop, including food crops, may be grown with reclaimed wastewater after suitable preapplication treatment.

In areas with a long growing season, such as California, selection of a double crop is an excellent means of increasing the revenue potential as well as the annual consumptive water use and nitrogen uptake of the crop system. Double crop combinations that are commonly used include (1) short season varieties of soybeans, silage corn, or sorghum as a summer crop; and (2) barley, oats, wheat, vetch, or annual forage grass as a winter crop.

A growing practice in the East and Midwest is to provide a continuous vegetative cover with grass and corn. This “no-till” corn management consists of planting grass in the fall and then applying a herbicide in the spring before planting the corn. When the corn completes its growth cycle, grass is reseeded. Thus, cultivation is reduced; water use is maximized; nutrient uptake is enhanced; and revenue potential is increased.

4.3.1.2 Forest Crops

The most common forest crops used in SR systems have been mixed hardwoods and pines. A summary of representative operational systems and types of forest crops used is presented in Table 4-9.

The growth responses of a number of tree species to a range of wastewater loadings are identified in Table 4-10. The high growth response column is most suitable for wastewater application because of nitrogen uptake and productivity. The growth response will vary in accordance with a number of factors; one of the most important is the adaptability of the selected species to the local climate. Local foresters should be consulted for specific judgments on the likely response of selected species.

TABLE 4-9
SUMMARY OF OPERATIONAL FOREST LAND TREATMENT SYSTEMS IN THE UNITED STATES RECEIVING MUNICIPAL WASTEWATER

Location	Flow, m^3/d	Forest type	Date started	Hydraulic loading, cm/wk	Other conditions
Clayton County, Georgia	73,800	Loblolly pine plantation and natural hardwood	1981	6.3	Ground water to be recycled as drinking water
Helen, Georgia	76	Mixed hardwood and pine	1973	7.6	--
Kings Bay Submarine Support Base, St. Marys, Georgia	1,250	Slash pine plantation	1981	1.3	Site drainage with open ditches
Mackinaw City, Michigan	760	Aspen, white pine birch	1976	11.3	Frost free, seasonal application
Mt. Sunapee State Park, Newbury, New Hampshire	26	Mixed hardwood	1971	5.0	Water stored and applied in June and July only
State College, Pennsylvania (Penn State University)	11,350	Mixed hardwood; red pine plantation; spruce, old field	1963	2.0-7.5	Ground water to be recycled as drinking water
West Dover, Vermont	2,080	Northern hardwoods; balsam, hemlock, spruce in understory	1976	≤6.3	Operates at air temperatures above -18 °C

TABLE 4-10
HEIGHT GROWTH RESPONSE OF SELECTED TREE SPECIES [Adapted from 19]

Height growth response class		
Low	Intermediate	High
Slash pine	Tulip poplar	Cottonwood
Cherry-laurel	Bald cypress	Sycamore
Arizona cypress	Saw-tooth oak	Green ash
Live oak	Red cedar	Black cherry
Holly	Laurel oak	Sweetgum
Hawthorne	Magnolia	Black locust
Northern white cedar	Nuttall oak	Red bud
Red pine	Cherry bark oak	Catalpa
	Loblolly pine	Chinese elm
	Shortleaf pine	White pine
	Virginia pine	
	Douglas-fir	

4.3.2 Crop Characteristics

Reference data and information on the crop characteristics of (1) nutrient uptake, water quality requirements, and toxicity concerns; (2) water tolerance; (3) consumptive water use; and (4) effect on soil hydraulic properties are presented in this section for both agricultural crops and forest crops.

4.3.2.1 Nutrient Uptake

Agricultural Crops

In general, the largest nutrient removals can be achieved with perennial grasses and legumes that are cut frequently at early stages of growth. It should be recognized that legumes can fix nitrogen from the air, but they are active scavengers for nitrate if it is present. The potential for harvesting nutrients with annual crops is generally less than with perennials because annuals use only part of the available growing season for growth and active uptake. Typical annual uptake rates of the major plant nutrients--nitrogen, phosphorus, and potassium--are listed in Table 4–11 for several commonly selected crops.

The nutrient removal capacity of a crop is not a fixed characteristic but depends on the crop yield and the nutrient content of the plant at the time of harvest. Design estimates of harvest removals should be based on yield goals and nutrient compositions that local experience indicates can be achieved with good management on similar soils.

TABLE 4-11
NUTRIENT UPTAKE RATES FOR SELECTED CROPS
kg/ha•yr

	Nitrogen	Phosphorus	Potassium
Forage crops			
Alfalfa[a]	225-540	22-35	175-225
Bromegrass	130-225	40-55	245
Coastal bermudagrass	400-675	35-45	225
Kentucky bluegrass	200-270	45	200
Quackgrass	235-280	30-45	275
Reed canarygrass	335-450	40-45	315
Ryegrass	200-280	60-85	270-325
Sweet clover[a]	175	20	100
Tall fescue	150-325	30	300
Orchardgrass	250-350	20-50	225-315
Field crops			
Barley	125	15	20
Corn	175-200	20-30	110
Cotton	75-110	15	40
Grain sorghum	135	15	70
Potatoes	230	20	245-325
Soybeans[a]	250	10-20	30-55
Wheat	160	15	20-45

a. Legumes will also take nitrogen from the atmosphere.

The rate of nitrogen uptake by crops changes during the growing season and is a function of the rate of dry matter accumulation and the nitrogen content of the plant. Consequently, the pattern of nitrogen uptake is subject to many environmental and management variables and is crop specific. Examples of measured nitrogen uptake rates versus time are shown in Figure 4-2 for annual crops and perennial forage grasses receiving wastewater.

The amounts of phosphorus in applied wastewaters are usually much higher than plant requirements. Fortunately, most soils have a high sorption capacity for phosphorus and very little of the excess passes through the soil (see Section 4.2.3).

Potassium is used in large amounts by many crops, but typical wastewater is relatively deficient in this element. In most cases, fertilizer potassium may be needed to provide for optimal plant growth, depending on the soil and crop grown (see Section 4.9.1.2). Other macronutrients taken up by crops include magnesium, calcium and sulfur; deficiencies of these nutrients are possible in some areas.

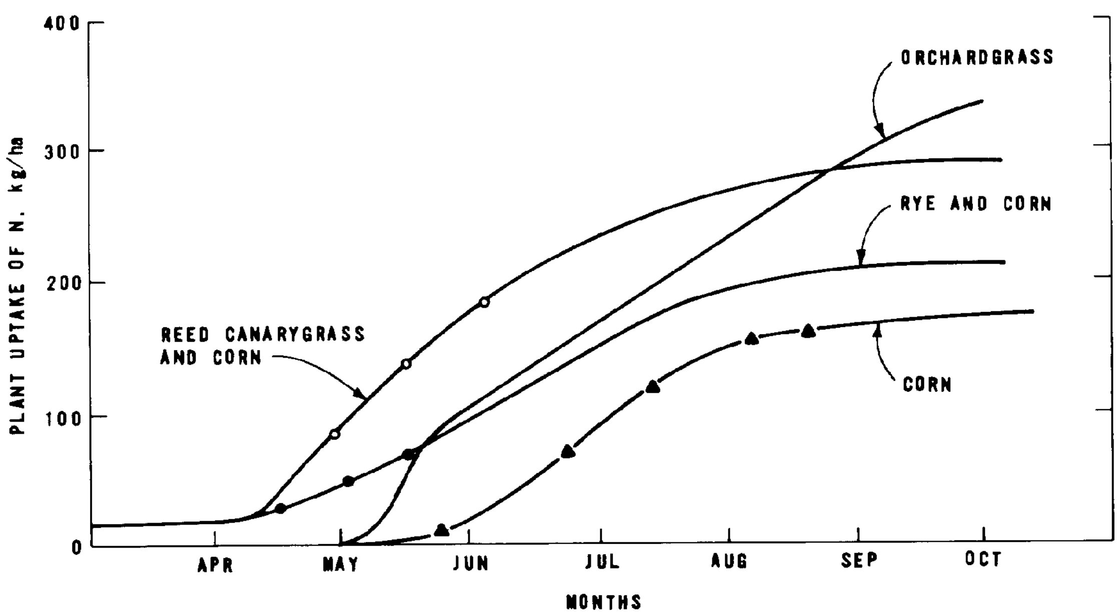


FIGURE 4-2
NITROGEN UPTAKE VERSUS GROWING DAYS
FOR ANNUAL AND PERENNIAL CROPS [20,21]

The micronutrients important to plant growth (in descending order) are: iron, manganese, zinc, boron, copper, molybdenum, and, occasionally, sodium, silicon, chloride, and cobalt. Most wastewaters contain an ample supply of these elements; in some cases, phytotoxicity may be a consideration.

Forest Crops

Vegetative uptake and storage of nutrients depend on the species and forest stand density, structure, age, length of season, and temperature. In addition to the trees, there is also nutrient uptake and storage by the understory tree and herbaceous vegetation. The role of the understory vegetation is particularly important in the early stages of tree establishment.

Forests take up and store nutrients and return a portion of those nutrients back to the soil in the form of leaf fall and other debris such as dead trees. Upon decomposition, the nutrients are released and the trees take them back up. During the initial stages of growth (1 to 2 years), tree seedlings are establishing a root system; biomass production and nutrient uptake are relatively slow. To prevent leaching of nitrogen to ground water during this period, nitrogen loading must be limited or understory vegetation must be established that will take up and store applied nitrogen that is in excess of the tree crop needs. Management of understory vegetation is discussed in Section 4.9.

Following the initial growth stage, the rates of growth and nutrient uptake increase and remain relatively constant until maturity is approached and the rates decrease. When growth rates and nutrient uptake rates begin to decrease, the stand should be harvested or the nutrient loading decreased. Maturity may be reached at 20 to 25 years for southern pines, 50 to 60 years for hardwoods, and 60 to 80 years for some of the western conifers such as Douglasfir. Of course, harvesting may be practiced well in advance of maturity as with short-term rotation management (see Section 4.9.2.5).

Estimates of the net annual nitrogen storage for a number of fully stocked forest ecosystems are presented in Table 4-12. These estimates are maximum rates of net nitrogen uptake considering both the understory and overstory vegetation during the period of active tree growth.

TABLE 4-12
ESTIMATED NET ANNUAL NITROGEN UPTAKE IN THE OVERSTORY AND UNDERSTORY VEGETATION OF FULLY STOCKED AND VIGOROUSLY GROWING FOREST ECOSYSTEMS IN SELECTED REGIONS OF THE UNITED STATES [22]

	Tree age, yr	Average annual nitrogen uptake, kg/ha·yr
Eastern forests		
Mixed hardwoods	40-60	220
Red pine	25	110
Old field with white spruce plantation	15	280
Pioneer succession	5-15	280
Southern forests		
Mixed hardwoods	40-60	340
Southern pine with no understory	20	220[a]
Southern pine with understory	20	320
Lake states forests		
Mixed hardwoods	50	110
Hybrid poplar[b]	5	155
Western forests		
Hybrid poplar[b]	4-5	300-400
Douglas-fir plantation	15-25	150-250

a. Principal southern pine included in these estimates is loblolly pine.

b. Short-term rotation with harvesting at 4-5 yr; represents first growth cycle from planted seedlings (see Section 4.9.2.4).

Because nitrogen stored within the biomass of trees is not uniformly distributed among the tree components, the amount of nitrogen that can actually be removed with a forest crop system will be substantially less than the storage estimates given in Table 4-12 unless 100% of the aboveground biomass is harvested (whole–tree harvesting). If only the merchantable stems are removed from the system, the net amount of nitrogen removed by the system will be less than 30% of the amount stored in the biomass. The distributions of biomass and nitrogen for naturally growing hardwood and conifer (pines, Douglas-fir, fir, larch, etc.) stands in temperate regions are shown in Table 4-13. For deciduous species, whole-tree harvesting must take place in the summer when the leaves are on the trees if maximum nitrogen removal is to be achieved.

TABLE 4-13
BIOMASS AND NITROGEN DISTRIBUTIONS BY TREE COMPONENT FOR STANDS IN TEMPERATE REGIONS [23]
Percent

	Conifers		Hardwoods	
Tree component	Biomass	Nitrogen	Biomass	Nitrogen
Roots	10	17	12	18
Stems	80	50	65	32
Branches	8	12	22	42
Leaves	2	20	1	8

The assimilative capacity for both phosphorus and trace metals is controlled more by soil properties than plant uptake. The relatively low pH (4.2 to 5.5) of most forest soils is favorable to the retention of phosphorus but not trace metals. However, the high level of organic matter in forest soil improves the metal removal capacity. The amount of phosphorus in trees is small, usually less than 30 kg/ha (27 lb/acre); therefore, the amount of annual phosphorus accumulation is quite small.

4.3.2.2 Moisture Tolerance

Crops that can be exposed to prolonged periods of high soil moisture without suffering damage or yield reduction are said to have a high moisture or water tolerance. This characteristic is desirable in situations (1) where hydraulic loading rates must be maximized, (2) where the root zone contains a slowly permeable soil, or (3) in humid areas where sufficient moisture already exists for plant growth. Refer to Table 4-8 for a comparison of crop moisture tolerances. Alfalfa and red pine, for example, have low moisture tolerances.

4.3.2.3 Consumptive Water Use

Consumptive water use by plants is also termed evapotranspiration (ET). Consumptive water use varies with the physical characteristics and the growth stage of the crop, the soil moisture level, and the local climate. In some states, estimates of maximum monthly consumptive water use for many crops can be obtained from local agricultural extension offices or research stations or the SCS. Where this information is not available, it will be necessary to make estimates of evapotranspiration using temperature and other climatic data. Several methods of estimating evapotranspiration are available and are detailed in publications by the American Society of Civil Engineers (ASCE) [24], the Food and Agriculture Organization (FAO) of the United Nations [25], and the SCS [26].

Agricultural Crops

In humid regions estimates of potential evapotranspiration (PET) are usually sufficient for perennial, full-cover crops. Examples of estimated PET for humid and subhumid climates are shown in Table 4-14. Examples of monthly consumptive use in arid regions are shown in Table 4-15 for several California crops. These table values are specific for the location given and are intended to illustrate variation in ET due to crop and climate. The designer should obtain or estimate ET values that are specific to the site under design.

TABLE 4-14
EXAMPLES OF ESTIMATED MONTHLY POTENTIAL EVAPOTRANSPIRATION FOR HUMID AND SUBHUMID CLIMATES
cm

Month	Paris, Texas	Central Missouri	Brevard, North Carolina	Jonesboro, Georgia	Hanover, New Hampshire	Seabrook, New Jersey
Jan	1.5	0.7	0.2	1.3	0.0	0.2
Feb	1.5	1.3	0.3	1.3	0.0	0.3
Mar	3.6	3.0	2.1	3.0	0.1	2.0
Apr	6.8	6.6	4.6	5.8	2.9	4.0
May	9.9	10.8	7.6	10.9	8.2	7.4
Jun	14.7	14.5	10.2	14.7	12.9	11.4
Jul	16.0	16.9	11.4	15.7	13.7	13.9
Aug	16.2	15.2	10.4	15.0	11.9	13.6
Sep	9.7	10.3	7.4	10.9	7.4	9.9
Oct	6.4	6.3	4.6	5.8	4.0	4.9
Nov	2.7	2.6	1.6	2.5	0.3	2.1
Dec	1.4	1.1	0.3	1.3	0.0	0.3
Annual	90.4	89.3	60.7	88.2	61.4	70.0

In arid or semiarid regions, water in excess of consumptive use must be applied to (1) ensure proper soil moisture conditions for seed germination, plant emergence, and root development; (2) flush salts from the root zone; and (3) account for nonuniformity of water application by the distribution system (see Section 4.7). This requirement is the irrigation requirement and examples are shown in Table 4-15. Local irrigation specialists should be consulted for specific values.

TABLE 4-15
CONSUMPTIVE WATER USE AND IRRIGATION REQUIREMENTS FOR SELECTED CROPS AT SAN JOAQUIN VALLEY, CALIFORNIA[a] [27, 28]
Depth of Water in cm

	Pastures or alfalfa[b]		Double crop barley and grain sorghum[c]		Cotton[d]		Sugar beets[e]	
Month	Consumptive use	Irrigation requirements	Consumptive use	Irrigation requirements	Consumptive use	Irrigation requirements	Consumptive use	Irrigation requirements
Jan	2.3	3.0	2.5	--	--	--	--	--
Feb	5.1	6.9	5.1	--	--	38.1[f]	--	--
Mar	9.7	13.0	9.7	15.2	--	--	--	12.7
Apr	13.2	17.8	13.2	15.2	1.5	--	2.5	22.9
May	17.8	23.9	6.6	--	3.0	--	6.4	12.7
Jun	21.8	29.2	--	25.4[g]	9.1	12.7	12.7	22.9
Jul	23.9	32.0	11.4	17.8	18.3	30.5	17.8	19.1
Aug	22.1	29.7	20.3	30.1	21.3	30.5	20.3	11.4
Sep	14.7	19.8	15.2	22.9	15.2	--	--	--
Oct	10.9	14.7	7.6	--	6.4	--	--	--
Nov	5.1	6.9	--	--	--	--	--	15.2[g]
Dec	2.5	3.3	2.5	25.4	--	--	--	--
Total	149.1	200.2	94.1	152.0	74.8	111.8	59.7	116.9

a. Other crops having similar growing seasons and ground cover will have similar consumptive use.

b. Estimated maximum consumptive use (evapotranspiration) of water by mature crops with nearly complete ground cover throughout the year.

c. Barley planted in November-December, harvested in June. Grain sorghum planted June 20-July 10, harvested in November-December.

d. Rooting depth of mature cotton: 1.8 m. Planting dates: March 15 to April 20. Harvest: October, November, and December.

e. Rooting depth: 1.5 to 1.8 m. Planting date: January. Harvest: July 15 to September 10.

f. Preirrigation should wet soil to 1.5 to 1.8 m depth prior to planting.

g. Preirrigation is used to ensure germination and emergence. First crop irrigations are heavy in order to provide deep moisture.

Forest Crops

The consumptive water use of forest crops under high soil moisture conditions may exceed that of forage crops in the same area by as much as 30%. For design purposes, however, the potential ET is used because there is little information on water use of different forest species. The seasonal pattern of water use for conifers is more uniform than for deciduous trees.

4.3.2.4 Effect on Soil Hydraulic Properties

In general, plants tend to increase both the infiltration rate of the soil surface and the effective hydraulic conductivity of the soil in the root zone as a result of root penetration and addition of organic matter. The magnitude of this effect varies among different crops. Thus, the crop selected can affect the design application rate of sprinkler distribution systems, which is based on the steady state infiltration rate of the soil surface. Steady state infiltration rate is equivalent to the saturated permeability of surface soil. Design sprinkler application rates can be increased by 50% over the permeability value for most full-cover crops and by 100% for mature (>4 years old), well-managed permanent pastures (see Appendix E). The design application rate (cm/h or in./h) should not be confused with hydraulic loading rate (cm/wk or cm/mo) which is based on the permeability of the most restrictive layer in the soil profile. This layer, in many cases, is below the root zone and is unaffected by the crop.

Forest surface soils are generally characterized by high infiltration capacities and high porosities due to the presence of high levels of organic matter. The infiltration rates of most forest surface soils exceed all but the most extreme rainfall intensities. Therefore, surface infiltration rate is not usually a limiting factor in establishing the design application rate for sprinkler distribution in forest systems.

In addition, the permeability of subsurface forest soil horizons is generally improved over that found under other vegetation systems because there is: (1) no tillage, (2) minimum compaction from vehicular traffic, (3) decomposition of deep penetrating roots, and (4) a well-developed structure due to the increased organic matter content and microbial activity. Where subfreezing temperatures are encountered, the forest floor serves to insulate the soil so that soil freezing, if it does occur, occurs slowly and does not penetrate deeply. Consequently, wastewater application can often continue through the winter at forest systems.

4.3.2.5 Crop Water Quality Requirements and Toxicity Concerns

Wastewaters may have constituents that: (1) are harmful to plants (phytotoxic), (2) reduce the quality of the crop for marketing, or (3) can be taken up by plants and result in a toxic concern in the food chain. Thus, the effect of wastewater constituents on the crop itself and the potential for toxicity to plant consumers must be considered during the crop selection process. Agricultural crops are of primary concern.

A summary of common wastewater constituents that can adversely affect certain crops either through a direct toxic effect or through degradation of crop quality is given in Table 4–16. Also indicated in the table are the constituent concentrations at which problems occur. These effect are discussed in further detail in Chapter 9.

TABLE 4-16
SUMMARY OF WASTEWATER CONSTITUENTS
HAVING POTENTIAL ADVERSE EFFECTS
ON CROPS [29]

Problem and related constituent	Constituent level: No problem	Increasing problems	Severe problems	Crops affected
Salinity (EC_w), mmho/cm	<0.75	0.75-3.0	>3.0	Crops in arid climates only (see Table 9-4)
Specific ion toxicity from root absorption				
Boron, mg/L	<0.5	0.5-2	2.0-10.0	Fruit and citrus trees - 0.5-1.0 mg/L; field crops - 1.0-2.0 mg/L; grasses - 2.0-10.0 mg/L
Sodium, adj-SAR[a]	<3	3.0-9.0	>9.0	Tree crops
Chloride, mg/L	<142	142-355	>355	Tree crops
Specific ion toxicity from foliar absorption				
Sodium, mg/L	<69	>69	--	Field and vegetable crops under sprinkler application
Chloride, mg/L	<106	>106	--	
Miscellaneous				
NH_4-N + NO_3-N, mg/L	<5	5-30	30	Sugarbeets, potatoes, cotton, grains
HCO_3, mg/L	<90	90-520	>520	Fruit
pH, units	6.5-8.4	4.2-5.5	<4.2 and >8.5	Most crops

a. Adjusted sodium adsorption ratio.

Trace elements, particularly zinc, copper, and nickel are of concern for phytotoxicity. However, the concentration of these elements in wastewaters is well below the toxic level of all crops and phytotoxicity could only occur as a result of long-term accumulation of these elements in the soil.

4.4 Preapplication Treatment

Preapplication treatment is provided for three reasons:

1. Protection of public health as it relates to human consumption of crops or crop byproducts or to direct exposure to applied wastewater

2. Prevention of nuisance conditions during storage

3. Prevention of operating problems in distribution systems

Preapplication treatment is not necessary for the SR process to achieve maximum treatment, except in the case of harmful or toxic constituents from industrial sources (see Section 4.4.3). The SR process is capable of removing high levels of most constituents present in municipal wastewaters, and maximum use should be made of this renovative capacity in a complete treatment system. Therefore, the level of preapplication treatment provided should be the minimum necessary to achieve the three stated objectives. In general, any additional preapplication treatment will result in higher costs and energy use.

The EPA has issued general guidelines for assessing the level of preapplication treatment necessary for SR systems [30]. The guidelines are intended to provide adequate protection for public health:

A. Primary treatment - acceptable for isolated locations with restricted public access and when limited to crops not for direct human consumption.

B. Biological treatment by ponds or inplant processes plus control of fecal coliform count to less than 1,000 MPN/100 mL - acceptable for controlled agricultural irrigation except for human food crops to be eaten raw.

C. Biological treatment by ponds or inplant processes with additional BOD or SS control as needed for aesthetics plus disinfection to log mean of 200/100 mL (EPA fecal coliform criteria for bathing waters) - acceptable for application in public access areas such as parks and golf courses.

In most cases, state or local public health or water quality control agencies regulate the quality of municipal wastewater that can be used for SR. The appropriate state and local agencies should be contacted early in the design process to determine specific restrictions on the quality of applied wastewater.

4.4.1 Preapplication Treatment for Storage and During Storage

Objectionable odors and nuisance conditions can occur if anaerobic conditions develop near the surface in a storage pond. Two preapplication treatment options are available to prevent odors:

1. Reduce the oxygen demand of the wastewater prior to storage.

2. Design the storage pond as a deep facultative pond, using appropriate BOD loading.

Complete biological treatment and disinfection are unnecessary prior to storage. The level of treatment provided should not exceed that necessary to control odors. For storage ponds with short detention times (less than 10 to 15 days), a reduction in the BOD of the wastewater to a range of 40 to 75 mg/L should be sufficient to prevent odors. An aerated cell is are normally used for BOD reduction in such cases. For storage ponds with longer detention times, BOD reduction before storage is normally not required because the storage pond is serving as a stabilization pond.

Wastewater undergoes treatment during storage. Suspended solids, oxygen demand, nitrogen, and microorganisms are reduced. In general, the extent of reduction depends on the length of the storage period. In the case of nitrogen, removal during storage can affect the design and operation of the SR process because the allowable hydraulic loading rate may be governed by the nitrogen concentration of the applied wastewater. Nitrogen removal in storage reservoirs can be substantial and depends on several factors including detention time, temperature, pH, and pond depth. A preliminary model to estimate nitrogen removals in ponds during ice–free periods has been developed [31]:

$$N_t = N_0 e^{-0.0075t} \tag{4-1}$$

where N_t = nitrogen concentration in pond effluent (total N), mg/L

N_o = nitrogen concentration entering pond (total N), mg/L

t = detention time, d

A more precise model for predicting ammonia nitrogen removals in ponds is presented in the Process Design Manual on Wastewater Treatment ponds [32].

Nitrogen in pond effluent is predominantly in the ammonia or organic form. In most cases, it is desirable to apply nitrogen in these forms to SR systems because they are held at least temporarily in the soil profile and are available for plant uptake for longer periods than nitrate, which is mobile in the soil profile. Ammonia and organic nitrogen which is converted to ammonia, are particularly desirable in forest systems because many tree species do not take up nitrate as efficiently as ammonia.

A model describing the removal of fecal coliforms in pond systems has also been developed [33]:

$$C_f = C_i\ e^{-Kt2^{(T-20)}} \qquad (4\text{–}2)$$

where C_f = effluent fecal coliform concentration, No./100 mL

C_i = entering fecal coliform concentration, No./100 mL

K = 0.5 warm months; 0.03 cold months

t = "actual" detention time, d

2 = 1.072

T = liquid temperature, °C

Based on this model, actual detention times of about 17 days and 21 days would be necessary at 20 °C (68 °F) to reduce the coliform level of a typical domestic wastewater to 1,000/100 mL and 200/100 mL, respectively. Thus, effluent from storage reservoirs, in many cases, may meet the EPA coliform recommendations for SR systems without disinfection.

Removal of viruses in ponds is also quite rapid at warm temperatures. Essentially complete removal of Coxsackie and polio viruses was observed after 20 days at 20 °C [34]

4.4.2 Preapplication Treatment to Protect Distribution Systems

Deposition of settleable solids and grease in distribution laterals or ditches can cause reduction in the flow capacity of the distribution network and odors at the point of application. Coarse solids can cause severe clogging problems in sprinkler distribution systems. Removal of settleable solids and oil and grease (i.e., primary sedimentation or equivalent) is therefore recommended as a minimum level of preapplication treatment. For sprinkler systems, it has been recommended that the size of the largest particle in the applied wastewater be less than one-third the diameter of the sprinkler nozzle to avoid plugging.

4.4.3 Industrial pretreatment

Pollutants that are compatible with conventional secondary treatment systems would generally be compatible with land treatment systems. As with conventional systems, pretreatment requirements will be necessary for such constituents as fats, grease and oils, and sulfides to protect collection systems and treatment components. Pretreatment requirements for conventional biological treatment will also be sufficient for land treatment processes.

4.5 Loading Rates and Land Area Requirements

The hydraulic loading rate is the volume of wastewater applied per unit area of land over at least one loading cycle. Hydraulic loading rate is commonly expressed in cm/wk or in/yr (in./wk or ft/yr) and is used to compute the land area required for the SR process. The hydraulic loading rate used for design is based on the more restrictive of two limiting conditions——the capacity of the soil profile to transmit water (soil permeability) or the nitrogen concentration in water percolating beyond the root zone.

A separate case is considered for those systems in arid regions where crop revenue is important and the wastewater is used as a valuable source of irrigation water. For such systems, the design hydraulic loading rate is usually based on the irrigation requirements of the crop.

4.5.1 Hydraulic Loading Rate Based on Soil permeability

The general water balance equation with rates based on a monthly time period is the basis of this procedure. The equation, with runoff of applied water assumed to be zero, is:

$$L_w = ET - Pr + P_w \qquad (4\text{-}3)$$

where L_w = wastewater hydraulic loading rate

ET = evapotranspiration rate

Pr = precipitation rate

P_w = percolation rate

The basic steps in the procedure are:

1. Determine the design precipitation for each month based on a 5 year return period frequency analysis for monthly precipitation. Alternatively, use a 10 year return period for annual precipitation and distribute it monthly based on the ratio of average monthly to average annual precipitation.

2. Estimate the monthly ET rate of the selected crop (see Section 4.3.2.3).

3. Determine by field test the minimum clear water permeability of the soil profile. If the minimum soil permeability is variable over the site, determine an average minimum permeability based on areas of different soil types.

4. Establish a maximum daily design percolation rate that does not exceed 4 to 10% of minimum soil permeability (see Figure 2–3). Percentages on the lower end of the scale are recommended for variable or poorly defined soil conditions. The percentage to use is a judgment decision to be made by the designer. The daily percolation rate is determined as follows:

   $P_{w(daily)}$ = permeability, cm/h (24 h/d)(4 to 10%)

5. Calculate the monthly percolation rate with adjustments for those months having periods of nonoperation. Nonoperation may be due to:

   ! Crop management. Downtime must be allowed for harvesting, planting, and cultivation as applicable.

   ! Precipitation. Downtime for precipitation is already factored into the water balance computation. No adjustments are necessary.

   ! Freezing temperatures. Subfreezing temperatures cause soil frost that reduces surface infiltration rate. Operation is usually stopped when this occurs. The most conservative approach to adjusting the monthly percolation rate for freezing conditions is to allow no operation for days during the month when the mean temperature is less than 0 °C (32 °F). A less conservative approach is to use a lower minimum temperature. The recommended lowest mean temperature for operation is -4 °C (25 °F). Data sources and procedures for determining the number of subfreezing days during a month are presented in Sections 2.2.1.3, 2.2.2.2, and 4.6. Nonoperating days due to freezing conditions may also be estimated using the EPA-l computer program without precipitation constraints (see Section 4.6.2). For forest crops, operation can often continue during subfreezing conditions.

! Seasonal crops. When single annual crops are grown, wastewater is not normally applied during the winter season, although applications may occur after harvest and before the next planting. The design monthly percolation rate may be calculated as follows:

$$P_{w(monthly)} = [P_{w(daily)}] \times (\text{No. of operating d/mo})$$

6. Calculate the monthly hydraulic loading rate using Equation 4–3. The monthly hydraulic loadings are summed to yield the allowable annual hydraulic loading rate based on soil permeability [$L_{W(P)}$]. The computation procedure is illustrated by an example for both arid and humid climates in Table 4–17. The example is based on systems growing permanent pasture and having similar winter weather and soil conditions. Downtime is allowed for freezing conditions, but pasture management does not require harvesting downtime.

The allowable hydraulic loading rate based on soil permeability calculated by the above procedure $L_{w(P)}$ is the maximum rate for a particular site and operating conditions, and this rate will be used for design if there are no other constraints or limitations. If other limitations exist, such as percolate nitrogen concentration, it is necessary to calculate the allowable hydraulic loading rate based on these limitations and compare that rate with the $L_{w(P)}$. The lower of the two rates is used for design.

4.5.2 Hydraulic Loading Rate Based on Nitrogen Limits

In municipal wastewaters applied to SR systems, nitrogen is usually the limiting constituent when protection of potable ground water aquifers is a concern. If percolating water from an SR system will enter a potable ground water aquifer, then the system should be designed such that the concentration of nitrate nitrogen in the receiving ground water at the project boundary does not exceed 10 mg/L.

TABLE 4–17
WATER BALANCE TO DETERMINE HYDRAULIC LOADING RATES BASED ON SOIL PERMEABILITY
cm

Month	(2) ET, Evapotranspiration	(3) P_r, precipitation	(4)=(2)-(3) Net ET	(5) P_w, Percolation[a]	(6)=(4)+(5) $L_{w(p)}$, wastewater hydraulic loading
Arid climates					
Jan	2.3	3.0	-0.7	5.1	4.4
Feb	5.1	2.8	2.3	12.6	14.9
Mar	9.7	2.8	6.9	16.3	23.2
Apr	13.2	2.0	11.2	18.0	29.2
May	17.7	0.5	17.2	18.0	35.2
Jun	21.8	0.3	21.5	18.0	39.5
Jul	23.9	--	23.9	18.0	41.9
Aug	22.1	--	22.1	18.0	40.2
Sep	14.7	0.3	14.4	18.0	32.4
Oct	10.9	0.8	10.1	18.0	28.1
Nov	5.1	1.3	3.8	17.0	20.8
Dec	2.5	2.5	0.0	14.1	14.1
Annual	149.0	16.3	132.7	191.1	323.8
Humid climates					
Jan	1.3	13.5	-12.2	5.1	0.0[b]
Feb	1.3	13.0	-11.7	12.6	0.9
Mar	3.0	15.5	-12.5	16.3	3.8
Apr	5.8	11.3	- 5.5	18.0	12.5
May	10.9	11.1	- 0.2	18.0	17.8
Jun	14.7	11.7	3.0	18.0	21.0
Jul	15.7	13.3	2.4	18.0	20.4
Aug	15.0	11.1	3.9	18.0	21.9
Sep	10.9	9.1	1.8	18.0	19.8
Oct	5.8	8.0	- 2.2	18.0	15.8
Nov	2.5	8.0	- 5.5	17.0	11.5
Dec	1.3	12.8	-11.5	14.1	2.6
Annual	88.2	138.4	-50.2	191.1	148.0

a. Based on a soil profile with a moderately slow permeability (0.5 to 1.5 cm/h), $P_w(max)$ = (0.5 cm/h) (24 h/d) (30 d/mo) (0.05) = 18.0

b. L_w cannot be less than zero.

The approach to meeting this requirement involves first estimating an allowable hydraulic loading rate based on an annual nitrogen balance ($L_{w(n)}$), and comparing that to the previously calculated $L_{w(p)}$ to determine which value controls. The detailed steps in this procedure are:

1. Calculate the allowable annual hydraulic loading rate based on nitrogen limits using the following equation:

$$L_{w(n)} = \frac{(C_p)(Pr - ET) + (U)(10)}{(1-f)(C_n) - C_p} \qquad (4-4)$$

where $L_{w(n)}$ = allowable annual hydraulic loading rate based on nitrogen limits, cm/yr

C_p = nitrogen concentration in percolating water, mg/L

Pr = precipitation rate, cm/yr

ET = evapotranspiration rate, cm/yr

U = nitrogen uptake by crop, kg/ha•yr (Tables 4-2, 4-11, 4-12)

C_n = nitrogen concentration in applied wastewater, mg/L (after losses in preapplication treatment)

f = fraction of applied nitrogen removed by denitrification and volatilization (4.2.2).

2. Compare the value of $L_{w(n)}$ with the value of $L_{w(p)}$ calculated previously (Section 4.5.1). If $L_{w(n)}$ is greater than $L_{w(p)}$, do not continue the procedure and use $L_{w(p)}$ for design. If $L_{w(n)}$ is less than or equal to $L_{w(p)}$, design should be based on $L_{w(n)}$. The value of $L_{w(n)}$ calculated in Step 1 above may be used to estimate land requirements for purposes of Phase 2 planning, but for final design the procedure outlined in Steps 3 and 4 should be used.

3. Calculate an allowable monthly hydraulic loading rate based on nitrogen limits using Equation 4–4 with monthly values for Pr, ET, and U. Monthly values for Pr and ET will have been determined previously for the water balance table (see Section 4.5.1). Monthly values for crop uptake (U) can be estimated by assuming that annual crop uptake is distributed monthly according to the same ratio as monthly to total growing season ET.

   If data on nitrogen uptake versus time, such as that shown in Figure 4–2, are available for the crops and climatic region specific to the project under design, then such information may be used to develop a more accurate estimate of monthly nitrogen uptake values.

4. Compare each monthly value of $L_{w(n)}$ with the corresponding monthly value of $L_{w(p)}$ calculated

previously (Section 4.5.1). The lower of the two values should be used for design. The design monthly hydraulic loading rates are summed to yield the design annual hydraulic loading rate.

The above procedure is illustrated in Example 4–1 for an arid climate and a humid climate using the climatic and operating conditions given in Table 4–17.

EXAMPLE 4-1: CALCULATION TO ESTIMATE DESIGN HYDRAULIC LOADING RATE

Conditions

		Humid climate	Arid climate
1.	Applied wastewater nitrogen concentration (C_n), mg/L	25	25
2.	Crop nitrogen uptake (U), kg/ha·yr	336	336
3.	Denitrification + volatilization (as a fraction of applied nitrogen)	0.2	0.2
4.	Limiting percolate nitrogen concentration (C_p), mg/L	10	10
5.	Precipitation (Pr) and evapotranspiration (ET) (see Table 4-17).		

Calculations

1. Calculate allowable annual $L_{w(n)}$ using Equation 4-4.

$$L_{w(n)} = \frac{(C_p)(Pr - ET) + (U)(10)}{(1 - f)(C_n) - C_p}$$

Humid climate

$$L_{w(n)} = \frac{(10)(138.4 - 88.2) + (336)(10)}{(1 - 0.2)(25) - 10}$$

$= 386.2$ cm/yr

Arid climate

$$L_{w(n)} = \frac{(10)(16.3 - 149) + (336)(10)}{(1 - 0.2)(25) - 10}$$

$= 203.3$ cm/yr

2. Compare $L_{w(n)}$ with $L_{w(p)}$.

Humid climate

$L_{w(n)} = 386.2$ cm/yr
$L_{w(p)} = 148.0$ cm/yr

$\therefore L_{w(p)}$ controls. Use $L_{w(p)}$ for design (see Table 4-17)

Arid climate

$L_{w(n)} = 203.3$ cm/yr
$L_{w(p)} = 323.8$ cm/yr

$\therefore L_{w(n)}$ controls. Continue to Step 3.

3. Compute allowable monthly $L_{w(n)}$ using Equation 4-4 and estimated monthly nitrogen uptake and monthly (Pr - ET) values. Compare with monthly $L_{w(p)}$ and use lower value for design. Tabulate results. (Arid climate only)

Month	(Pr - ET), cm	(U), kg/ha	$L_{w(n)}$, cm	$L_{w(p)}$, cm	Design L_w, cm
Jan	0.7	5.2	5.9	4.4	4.4
Feb	-2.3	11.5	9.2	17.5	9.2
Mar	-6.9	21.9	15.0	23.2	15.0
Apr	-11.2	29.8	18.6	29.2	18.6
May	-17.2	39.9	22.6	35.2	22.6
Jun	-21.5	49.2	27.6	39.5	27.6
Jul	-23.9	53.9	30.0	41.9	30.0
Aug	-22.1	49.8	27.9	40.2	27.9
Sep	-14.4	33.1	18.7	32.4	18.7
Oct	-10.1	24.6	14.5	28.1	14.5
Nov	-3.8	11.5	7.7	20.8	7.7
Dec	0.0	5.6	5.6	14.1	5.6
Annual	-132.7	336	203.3	323.8	201.8

The above procedure for calculating allowable hydraulic loading rate based on nitrogen limits is based on the following assumptions:

1. All percolate nitrogen is in the nitrate form.

2. No storage of nitrogen occurs in the soil profile.

3. No mixing and dilution of the percolate with in situ ground water occurs.

Use of these assumptions results in a very conservative estimate of percolate nitrogen. This procedure should ensure that the nitrogen concentration in the ground water at the project boundaries will be less than the specified value of C_p.

As indicated by the example, nitrogen loading is more likely to govern the design hydraulic loading rate for systems in arid climates than in humid climates. The reason for this is that the net positive ET rate in arid climates causes an increase in the concentration of the nitrogen level in the percolating water.

For systems in arid climates, it is possible that the design monthly hydraulic loading rates based on nitrogen limits will be less than the irrigation requirements (IR) of the crop. The designer should compare the design L_w with the irrigation requirement to determine if this situation exists. If it does exist, the designer has three options available to increase $L_{w(n)}$ sufficiently to meet the IR.

1. Reduce the concentration of applied nitrogen (C_n) through preapplication treatment.

2. Demonstrate that sufficient mixing and dilution (see Section 3.6.2) will occur with the existing ground water to permit higher values of percolate nitrogen concentration (C_p) to be used in Equation 4-4.

3. Select a different crop with a higher nitrogen uptake (U).

4.5.3 Hydraulic Loading Rate Based on Irrigation Requirements

For SR systems in arid regions that have crop production for revenue as the objective, the design hydraulic loading rate can be determined on the basis of the crop irrigation requirement (see Section 4.3.2.1) using a modified water balance equation:

$$L_w = IR - Pr \tag{4-5}$$

where L_w = hydraulic loading rate

IR = crop irrigation requirement

Pr = precipitation

The annual hydraulic loading rate is determined by summing the monthly hydraulic loading rates computed using Equation 4-5. The computational procedure is similar to that outlined in Section 4.5.1.

The monthly hydraulic loading rate based on IR should be checked against the allowable rate based on nitrogen limits ($L_{w(n)}$) as discussed in Section 4.5.2.

4.5.4 Land Area Requirements

The land area to which wastewater is actually applied is termed a field. In addition to the field area, the total land area required for an SR system includes land for preapplication treatment facilities, administration and maintenance buildings, service roads, buffer zones, and storage reservoir. Field area requirements and buffer zone requirements are discussed in this section. Storage area requirements are discussed in Section 4.6 and area requirements for preapplication treatment facilities, buildings, and service roads are determined by standard engineering practice not included in this manual.

4.5.4.1 Field Area Requirements

The required field area is determined from the design hydraulic loading rate according to the following equation:

$$A_w = \frac{(Q)(365)(d/yr) + \Delta V_s}{C(L_w)} \tag{4-6}$$

where A_w = field area, ha (acre)

Q = average daily community wastewater flow (annual basis), m^3/d (ft^3/d)

$)V_s$ = net loss or gain in stored wastewater volume due to precipitation, evaporation and seepage at storage pond, $m^3/yr (ft^3\ yr)$

C = constant, 100 (3,630)

L_w = design hydraulic loading rate, cm/yr (in./yr)

The first calculation of field area must be made without considering net gain or loss from storage. After storage pond area is computed, the value of $)V_s$ can be computed from precipitation and evaporation data. Field area then must be recalculated to account for $)V_s$.

Using the design hydraulic loading rate for the arid climate in Example 4-1, the field area for a daily wastewater flow of 1,000 m^3/d, neglecting $)V_s$, is:

$$A_w = \frac{(1,000)(365)}{(10^4)(201.8)(0.01)} = 18.1 \text{ ha}$$

4.5.4.2 Buffer Zone Requirements

The objectives of buffer zones around land treatment sites are to control public access, and in some cases, improve project aesthetics. There are no universally accepted criteria for determining the width of buffer zones around SR treatment systems. In practice, the widths of buffer zones range from zero for remote systems to 60 m (200 ft) or more for systems using sprinklers near populated areas. In many states, the width of buffer zones is prescribed by regulatory agencies and the designer should determine if such requirements exist.

The requirements for buffer zones in forest systems are generally less than those of other vegetation systems because forests reduce wind speeds and, therefore, the potential movement of aerosols. Forests also provide a visual screen for the public. A minimum buffer zone width of 15 m (50 ft) that is managed as a multistoried forest canopy will be sufficient to meet all objectives. The multistoried effect is achieved by maintaining mature trees on the inside edge of the buffer next to the irrigated area and filling beneath the canopy and out to the outside edge of the buffer with trees that grow to a moderate height and have full, dense canopies. Evergreen species are the best selection if year-round operation is planned. If existing natural forests are used for the buffer, a minimum width of 15 m may be sufficient to meet the objectives, if there is an adequate vegetation density.

4.6 Storage Requirements

In almost all cases, SR systems require some storage for periods when the amount of available wastewater flow exceeds the design hydraulic loading rate. The approach used to determine storage requirements is to first estimate a storage volume requirement using a water balance computation or computer programs developed to estimate storage needs based on observed climatic variations throughout the United States. The final design volume then is determined by adjusting the estimated volume for net gain or loss due to precipitation and evaporation using a monthly water balance on the storage pond. These estimating and adjustment procedures are described in the following sections.

Some states prescribe a minimum storage volume (e.g., 10 days storage). The designer should determine if such storage requirements exist.

All applied wastewater does not need to pass through the storage reservoir. In cases where primary effluent is suitable for application, only the water that must be stored need receive prestorage treatment. Stored and fresh wastewater is then blended for application.

4.6.1 Estimation of Volume Requirements Using Storage Water Balance Calculations

An initial estimate of the storage volume requirements may be determined using a water balance calculation procedure. The basic steps in the procedure are illustrated using the arid climate example from Example 4–1:

1. Tabulate the design monthly hydraulic loading rate as indicated in Table 4–17.

2. Convert the actual volume of wastewater available each month to units of depth (cm) using the following relationship.

$$W_a = \frac{(Q_m)(10^{-2})}{A_w} \qquad (4\text{-}7)$$

where W_a = depth of available wastewater, cm

Q_m = volume of available wastewater for the month, m^3

A_w = field area, ha

Insert the results for each month into a water balance table, as illustrated by the example in Table 4-18. In some communities, influent wastewater flow varies significantly with the time of year. The values used for Q_m should reflect monthly flow variation based on historical records. In this example, no monthly flow variation is assumed.

TABLE 4–18
ESTIMATION OF STORAGE VOLUME REQUIREMENTS
USING WATER BALANCE CALCULATIONS
cm

(1) Month	(2) L_w, wastewater hydraulic loading	(3) W_a, available wastewater[a]	(4) =(3)-(2) Change in storage	(5) Cumulative storage
Oct	14.5	16.8	2.3	-0.2[b]
Nov	7.7	16.8	9.1	2.3
Dec	5.6	16.8	11.2	11.4
Jan	4.4	16.8	12.4	22.6
Feb	9.2	16.8	7.6	35.0
Mar	15.0	16.8	1.8	42.6
Apr	18.6	16.8	- 1.8	44.4[c]
May	22.6	16.8	- 5.8	42.6
Jun	27.6	16.8	-10.8	36.8
Jul	30.0	16.8	-13.2	26.0
Aug	27.9	16.8	-11.1	12.8
Sep	18.7	16.8	- 1.9	1.7
Annual	201.8	201.6		

a. Based on a field area of 18.1 ha and 30,438 m^3/mo of wastewater.

b. Rounding error. Assume zero.

c. Maximum storage month.

3. Compute the net change in storage each month by subtracting the monthly hydraulic loading from the available wastewater in the same month.

4. Compute the cumulative storage at the end of each month by adding the change in storage during one month to the accumulated quantity from the previous month. The computation should begin with the reservoir empty at the beginning of the largest storage period. This month is usually October or November, but in some humid areas it may be February or March.

5. Compute the required storage volume using the maximum cumulative storage and the field area as indicated below.

   Required storage volume
   $= (44.4\ cm)\ (18.1\ ha)\ (10^{-2}\ m/cm)(10^{4}\ m^{2}\ /ha)$
   $= 8.04 \times 10^{4}\ m^{3}$

The advantage of using this water balance procedure to estimate storage volume requirements is that all factors that affect storage, including (1) seasonal changes in precipitation, evapotranspiration, and wastewater flow; and (2) downtime for precipitation or crop management are accounted for in the design hydraulic loading rate. The disadvantage of this procedure is that downtime for cold weather has to be determined separately and added in by reducing allowed monthly percolation.

4.6.2 Estimated Storage Volume Requirements Using Computer Programs

The National. Climatic Center in Asheville, North Carolina, has conducted an extensive study of climatic variations throughout the United States and the effect of these variations on storage requirements for soil treatment systems [35]. Based on this study, three computer programs, as presented in Table 4–19, have been developed to estimate the storage days required when inclement weather conditions preclude land treatment system operation.

TABLE 4-19
SUMMARY OF COMPUTER PROGRAMS FOR DETERMINING STORAGE FROM CLIMATIC VARIABLES [36]

EPA program	Applicability	Variables	Remarks
EPA-1	Cold climates	Mean temperature, rainfall, snow depth	Uses freeze index
EPA-2	Wet climates	Rainfall	Storage to avoid surface runoff
EPA-3	Moderate climates	Maximum and minimum temperature, rainfall, snow depth	Variation of EPA-1 for more temperate regions

Depending on the dominant climatic conditions of a region, one of the three computer programs will be most suitable. The program best suited to a particular region is shown in Figure 4-3. The storage days are calculated for recurrence intervals of 2, 4, 10, and 20 years. A list of stations

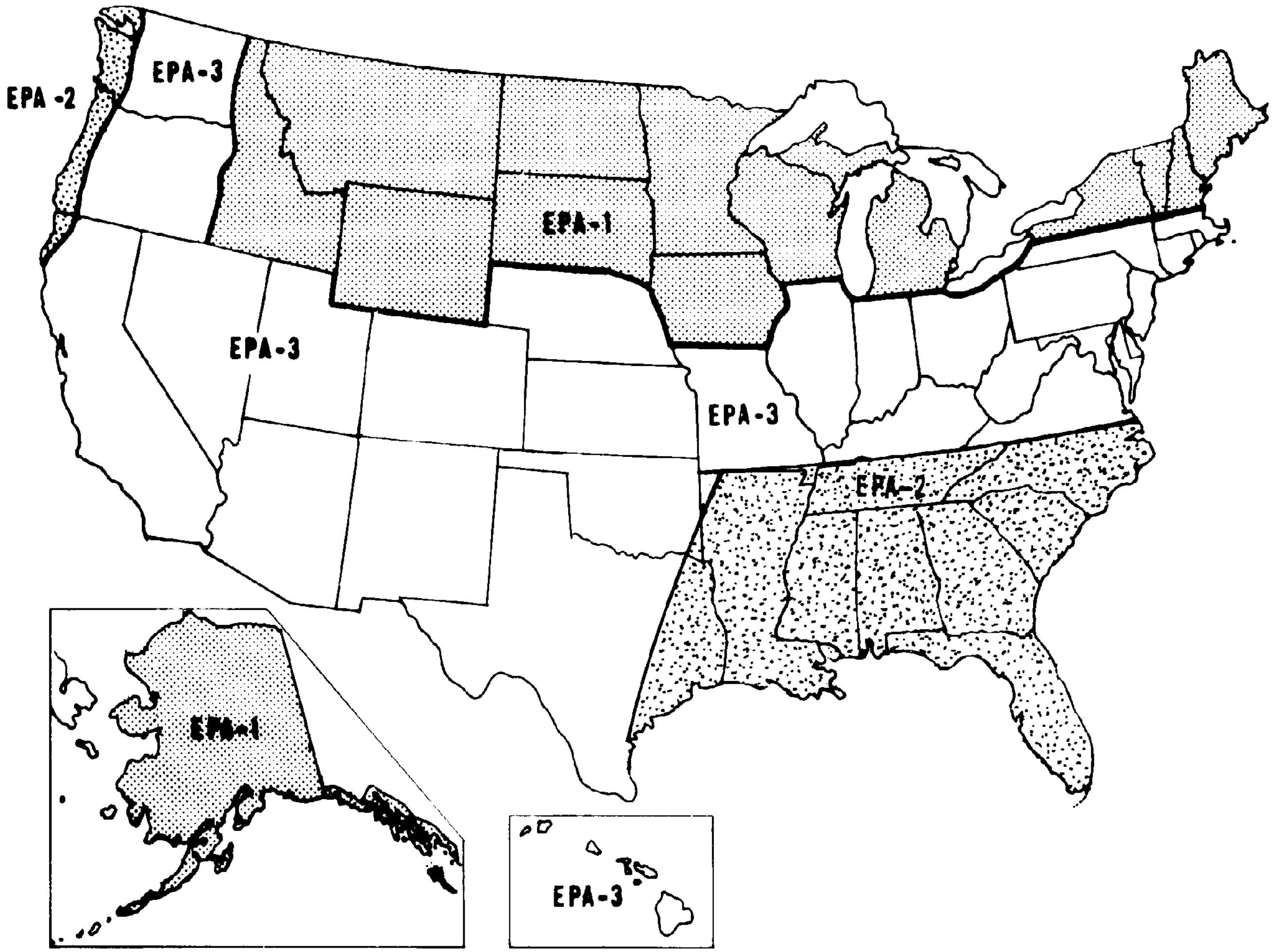


FIGURE 4-3
DETERMINATION OF STORAGE BY EPA COMPUTER PROGRAMS
ACCORDING TO CLIMATIC CONSTRAINTS

with storage days for 10 and 20 year recurrence intervals from EPA computer programs is presented in Appendix F. A list of 244 stations for which EPA-l has been run is included in reference [35]. To use these programs, contact the National Climatic Center of the National Oceanic and Atmospheric Administration in Asheville, North Carolina 28801; a fee is required.

Storage days required for crop management activities (harvesting, planting, etc.) must be added to the computer estimated storage days due to weather to obtain the total storage days required in each month. The estimated required storage volume is then calculated by multiplying the estimated number of storage days in each month times the average daily flow for the corresponding month.

4.6.3 Final Design Storage Volume Calculations

The estimated storage volume requirement obtained by water balance calculation or computer programs must be adjusted to account for net gain or loss in volume due to precipitation or evaporation. The mass balance procedure is Illustrated by Example 4-2 using arid climate data from Example 4-1 and the estimated storage volume from Table 4-18. An example for a system in a more humid climate is given in Appendix E.

EXAMPLE 4-2: CALCULATIONS TO DETERMINE FINAL STORAGE VOLUME REQUIREMENTS

1. Using the initial estimated storage volume and an assumed storage pond depth compatible with local conditions, calculate a required surface area for the storage pond:

$$A_s = \frac{V_{s(est)}}{d_s} \tag{4-8}$$

where A_s = area of storage pond, m^2

$V_{s(est)}$ = estimated storage volume, m^3

d_s = assumed pond depth, m

For the example, assume d_s = 4 m

$$A_s = \frac{(8.02 \times 10^4 \ m^3)}{4 \ m}$$

$$= 2 \times 10^4 \ m^2$$

2. Calculate the monthly net volume of water gained or lost from storage due to precipitation, evaporation, and seepage:

$$\Delta V_s = (Pr - E - seepage)(A_s)(10^{-2} \ m/cm) \tag{4-9}$$

where ΔV_s = net gain or loss in storage volume, m^3

Pr = design monthly precipitation, cm

E = monthly evaporation, cm

A_s = storage pond area

Estimated lake evaporation in the local area should be used for E, if available. Potential ET values may be used if no other data are available. Tabulate monthly values and sum to determine the net annual ΔV_s.

For example, assume:

E = ET

Seepage = 0

Results are tabulated in Column (2) of Table 4-20.

TABLE 4-20
FINAL STORAGE VOLUME REQUIREMENT CALCULATIONS
$m^3 \times 10^3$

Month	(2) ΔV_s Net gain/loss	(3) Q_m Available wastewater	(4) Vw Applied wastewater	(5) = (2) + (3) - (4) ΔV_s Change in storage	Cumulative storage
Oct	-2.0	30.4	24.3	4.1	-0.2[a]
Nov	-0.7	30.4	12.9	16.8	4.1
Dec	0.0	30.4	9.4	21.0	20.9
Jan	0.1	30.4	7.4	23.1	41.9
Feb	-0.5	30.4	15.4	14.5	65.0
Mar	-1.4	30.4	25.2	3.8	79.5
Apr	-2.2	30.4	31.2	-3.0	83.3[b]
May	-3.4	30.4	37.9	-10.9	80.3
Jun	-4.3	30.4	46.3	-20.2	69.4
Jul	-4.8	30.4	50.3	-24.7	49.2
Aug	-4.4	30.4	46.8	-20.8	24.5
Sep	-2.9	30.4	31.4	-3.9	3.7
Annual	-26.5	365	338.5		

a. Rounding error (assume zero).

b. Maximum design storage volume.

3. Tabulate the volume of wastewater available each month (Q_m) accounting for any expected monthly flow variations. For the example, monthly flow is constant.

$$Qm = \frac{(1{,}000 \text{ m}^3/\text{d})(365 \text{ d/yr})}{12 \text{ mo/yr}}$$
$$= 30.4 \times 10^3 \text{ m}^3/\text{mo}$$

4. Calculate an adjusted field area to account for annual net gain/loss in storage volume.

$$Aw' = \frac{\Sigma\Delta Vs + \Sigma Q_m}{(L_w)(10^4 \text{ m}^2/\text{ha})(10^{-2} \text{ m/cm})} \qquad (4\text{-}10)$$

where A_w' = adjusted field area, ha

$\Sigma\Delta Vs$ = annual net storage gain/loss, m^3

ΣQ_m = annual available wastewater, m^3

L_w = design annual hydraulic loading rate, cm

For the example:

$$A_w' = \frac{365 \times 10^3 - 26.5 \times 10^3}{(201.8)(10^4)(10^{-2})}$$
$$= 16.8 \text{ ha}$$

Note: The final design calculation reduced the field area from 18.1 ha to 16.8 ha.

5. Calculate the monthly volume of applied wastewater using the design monthly hydraulic loading rate and adjusted field area:

$$V_w = (L_w)(A_w')(10^4 \text{ m}^2/\text{ha})(10^{-2} \text{ m/cm}) \qquad (4\text{-}11)$$

where V_w = monthly volume of applied wastewater, m^3

L_w = design monthly hydraulic loading rate, cm

A_w' = adjusted field area, ha

Results are tabulated in Column (4) of Table 4-20.

6. Calculate the net change in storage each month by subtracting the monthly applied wastewater (V_w) from the sum of available wastewater (Q_m) and net storage gain/loss (ΔV_s) in the same month. Results are tabulated in Column (5) of Table 4-20.

7. Calculate the cumulative storage volume at the end of each month by adding the change in storage during one month to the accumulated total from the previous month. The computation should begin with the cumulative storage equal to zero at the beginning of the largest storage period. The maximum monthly cumulative volume is the storage volume requirement used for design.

Results are tabulated in Column (6) of Table 4-20.

$$\text{Design Vs} = 83.3 \times 10^3 \text{ m}^3$$

8. Adjust the assumed value of storage pond depth (d_s) to yield the required design storage volume using Equation 4-12.

$$d_s = V_s/A_s \tag{4-12}$$

For the example

$$d_s = \frac{83.3 \times 10^3\ m^3}{2 \times 10^4\ m^2}$$

$$= 4.16\ m$$

If the pond depth cannot be adjusted due to subsurface constraints, then the surface area must be adjusted to obtain the required design volume. However, if the surface area is changed, another iteration of the above procedure will be necessary because the value of net storage gain/loss (ΔV_s) will be different for a new pond area.

4.6.4 Storage Pond Design Considerations

Most agricultural storage ponds are constructed of homogeneous earth embankments, the design of which conforms to the principles of small dam design. Depending on the magnitude of the project, state regulations may govern the design. In California, for example, any reservoir with embankments higher than 1.8 m (6 ft) and a capacity in excess of 61,800 m^3 (50 acre-ft) is subject to state regulations on design and construction of dams, and plans must be reviewed and approved by the appropriate agency. Design criteria and information sources are included in the U.S. Bureau of Reclamation publication, Design of Small Dams [37]. In many cases, it will be necessary that a competent soils engineer be consulted for proper soils analyses and structural design of foundations and embankments.

In addition to storage volume, the principal design parameters are depth and area. The design depth and area depend on the function of the pond and the topography at the pond site. If the storage pond is to also serve as a facultative pond, then a minimum water depth of at least 0.5 to 1 m (1.5 to 3 ft) should be maintained in the pond when the stored volume is at a minimum. The area must also be sufficient to meet the BOD pond loading criteria for the local climate. The use of aerators can reduce area requirements. The maximum depth depends on whether the reservoir is constructed with dikes or embankments on level ground or is constructed by damming a natural water course or ravine. Maximum depths of diked ponds typically range from 3 to 6 m (9 to 18 ft). Other design considerations include wind fetch, and the need for riprap and lining. These aspects of design are covered in standard engineering references and assistance is also available from local SCS offices.

4.7 Distribution System

Design of the distribution system involves two steps: (1) selection of the type of distribution system, and (2) detailed design of system components. Emphasis in this section is placed on criteria for selection of the type of distribution system. Design procedures for SR distribution systems are presented in Appendix E. Only basic design principles for each type of distribution system are presented in the manual, and the designer is referred to several standard agricultural engineering references for further design details. Certain design requirements of distribution systems for forest crop systems do not conform to standard agricultural irrigation practice and are discussed under a separate heading.

4.7.1 Surface Distribution Systems

With surface distribution systems, water is applied to the ground surface at one end of a field and allowed to spread over the field by gravity. Conditions favoring the selection of a surface distribution system include the following:

1. Capital is not available for the initial investment required for more sophisticated systems.

2. Skilled labor is available at reasonable rates to operate a surface system.

3. Surface topography of land requires little additional preparation to make uniform grades for surface distribution.

The principal limitations or disadvantages of surface systems include the following:

1. Land leveling costs may be excessive on uneven terrain.

2. Uniform distribution cannot be achieved with highly permeable soils.

3. Runoff control and a return system must be provided when applying wastewater.

4. Skilled labor is usually required to achieve proper performance.

5. Periodic maintenance of leveled surface is required to maintain uniform grades.

Surface distribution systems may be classified into two general types: ridge and furrow and graded border (also termed bermed cell). The distinguishing physical features of these methods are illustrated in Figure 4-4. A summary of variations of the basic surface methods and conditions for their use is presented in Table 4-21. Details of preliminary design are presented in Appendix E.

4.7.2 Sprinkler Distribution Systems

Sprinkler distribution systems simulate rainfall by creating a rotating jet of water that breaks up into small droplets that fall to the field surface. The advantages and disadvantages of sprinkler distribution systems relative to surface distribution systems are summarized in Table 4-22.

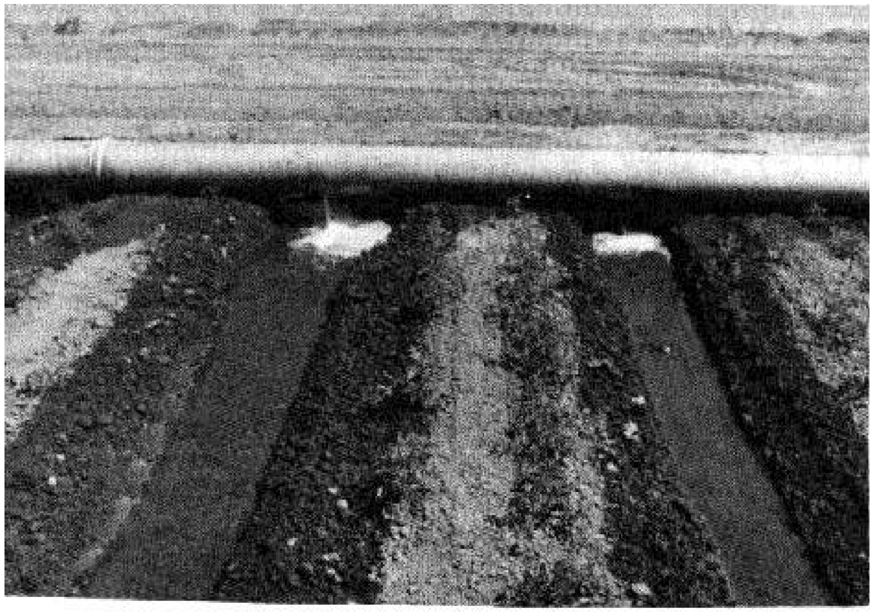
4.7.2.1 Types of Sprinkler Systems

In this manual, sprinkler systems are classified according to their movement during and between applications because this characteristic determines the procedure for design. There are three major categories of sprinkler systems based on movement:(1) solid set, (2) move-stop, and (3) continuous move. A summary of the various types of sprinkler systems under each category is given in Table 4-23 along with respective operating characteristics.

4.7.2.2 Sprinkler Distribution Systems for Forest

The requirements of distribution systems for forests are somewhat different from those for agricultural and turf crops. Solid—set irrigation systems are the most commonly used systems in forests. Buried systems are less susceptible to damage from ice and snow and do not interfere with forest management activities (thinning, harvesting, and regeneration). A center pivot irrigation system has been used in Michigan for irrigation of Christmas trees because their growth height would not exceed the height of the pivot arms. Traveling guns have also been used to irrigate short-term rotation hardwood plantations.

As discussed in Section 4.3.2.4, the design sprinkler application rate is usually not limited by the infiltration capacity of most forest soils. Steep grades (up to 35%), in general, do not limit the design hydraulic loading rate per application for forest systems. In fact, hydraulic loadings per application may be increased up to 10% on grades greater than 15% because of the higher drainage rate. Precautions must be taken to make sure that water draining through the surface soil does not appear as runoff further down the slope.



(a) RIDGE AND FURROW METHOD
USING GATED PIPE

(b) GRADED BORDER METHOD

FIGURE 4-4
SURFACE DISTRIBUTION METHODS

TABLE 4-21
SURFACE DISTRIBUTION METHODS AND CONDITIONS OF USE [38]

	Suitabilities and conditions of use				
Distribution	Crops	Topography	Water quantity	Soils	Remarks
Ridge and furrow					
Straight furrows	Vegetables, row crops, orchards, vineyards	Uniform grades not exceeding 2% for cultivated crops	Flows up to 0.34 m^3/s	Can be used on all soils if length of furrows is adjusted to type of soil	Best suited for crops that cannot be flooded. High irrigation efficiency possible. Well adapted to mechanized farming.
Graded contour furrows	Vegetables, field crops, orchards, vineyards	Undulating land with slopes up to 8%	Flows up to 0.08 m^3/s	Soils of medium to fine texture that do not crack on drying	Rodent control is essential. Erosion hazard from heavy rains or water breaking out of furrows. High labor requirement for irrigation.
Corrugations	Close-spaced crops such as grain, pasture, alfalfa	Uniform grades of up to 10%	Flows up to 0.03 m^3/s	Best on soils of medium to fine texture	High water losses possible from deep percolation or surface runoff. Care must be used in limiting size of flow in corrugations to reduce soil erosion. Little land grading required.
Basin furrows	Vegetables, cotton, maize, and other row crops	Relatively flat land	Flows up to 0.14 m^3/s	Can be used with most soil types	Similar to small rectangular basins, except crops are planted on ridges.
Zigzag furrows	Vineyards, bush berries, orchards	Uniform grades of less than 1%	Flows required are usually less than for straight furrows	Used on soils with low intake rates	This method is used to slow the flow of water in furrows to increase water penetration into soil.
Graded border					
Small rectangular basins	Grain, field crops, orchards, rice	Relatively flat land; area within each basin should be leveled	Can be adapted to streams of various sizes	Suitable for soils of high or low intake rates; should not be used on soils that tend to puddle	High installation costs. Considerable labor required for irrigating. When used for close-spaced crops, a high percentage of land is used for levees and distribution ditches. High efficiencies of water use possible.

Table 4-21 (Concluded)

Distribution	Suitabilities and conditions of use				Remarks
	Crops	Topography	Water quantity	Soils	
Large rectangular basins	Grain, field crops, rice	Flat land; must be graded to uniform plane	Large flows of water	Soils of fine texture with low intake rates	Lower installation costs and less labor required for irrigation than small basins. Substantial levees needed.
Contour checks	Orchards, grain, rice, forage crops	Irregular land, grades less than 2%	Flows greater than 0.03 m^3/s	Soils of medium to heavy texture that do not crack on drying	Little land grading required. Checks can be continuously flooded (rice), water ponded (orchards), or intermittently flooded (pastures).
Narrow borders up to 5 m wide	Pasture, grain, alfalfa, vineyards, orchards	Uniform grades less than 7%	Moderately large flows	Soils of medium to heavy texture	Borders should be in direction of maximum slope. Accurate cross-leveling required between guide levees.
Wide borders up to 30 m wide	Grain, alfalfa, orchards	Uniform grades less than 0.5%	Large flows, up to 0.56 m^3/s	Deep soils of medium to fine texture	Very careful land grading necessary. Minimum of labor required for irrigation. Little interference with use of farm machinery.
Benched terraces	Grain, field crops,	Grades up to 20%	Streams of small to medium size	Soils must be sufficiently deep that grading operations will not impair crop growth	Care must be taken in constructing benches and providing adequate drainage channel for excess water. Irrigation water must be properly managed. Misuse of water can result in serious soil erosion.

TABLE 4-22
ADVANTAGES AND DISADVANTAGES OF SPRINKLER DISTRIBUTION SYSTEMS RELATIVE TO SURFACE DISTRIBUTION SYSTEMS

Advantages	Disadvantages
1. Can be used on porous and variable soils.	1. Initial capital cost can be high.
2. Can be used on shallow soil profiles.	2. Energy costs are higher than for surface systems.
3. Can be used on rolling terrain.	3. Higher humidity levels can increase disease potential, for some crops.
4. Can be used on easily eroded soils.	4. Sprinkler application of high salinity water can cause leaf burn.
5. Can be used with small flows.	5. Water droplets can cause blossom damage to fruit crops or reduce the quality of some fruit and vegetable crops.
6. Skilled labor not required.	6. Portable or moving systems can get stuck in some clay soils.
7. Can be used where high water tables exist.	7. Higher levels of preapplication treatment generally are required for sprinkler systems than for surface systems to prevent operating problems (clogging).
8. Can be used for light, frequent applications.	8. Distribution is subject to wind distortion.
9. Control and measurement of applied water is easier.	9. Wind drift of sprays increases the potential for public exposure to wastewater.
10. Interference with cultivation is minimized.	
11. Higher application efficiencies are usually possible.	
12. Tailwater control and reapplication not usually required.	

TABLE 4-23
SPRINKLER SYSTEM CHARACTERISTICS

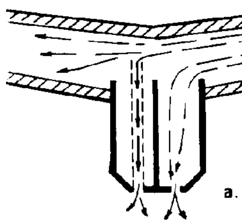
	Typical application rate, cm/h	Labor required per application, h/ha	Nozzle pressure range, N/cm^2	Size of single system, ha	Shape of field	Maximum grade, %	Maximum crop height, m
<u>Solid set</u>							
Permanent	0.13-5.08	0.02-0.04	21-69	Unlimited	Any shape	--	--
Portable	0.13-5.08	0.08-0.10	21-41	Unlimited	Any shape	--	--
<u>Move-stop</u>							
Hand move	0.03-5.08	0.2-0.6	21-41	<1-16	Any shape	20	--
End tow	0.03-5.08	0.08-0.16	21-41	8-16	Rectangular	5-10	--
Side wheel roll	0.25-5.08	0.04-0.12	21-41	8-32	Rectangular	5-10	1-1.2
Stationary gun	0.64-5.08	0.08-0.16	35-69	8-16	Any shape	20	--
<u>Continuous move</u>							
Traveling gun	0.64-2.54	0.04-0.12	35-69	16-41	Any shape	--	--
Center pivot	0.51-2.54	0.02-0.06	10-41	16-65	Circular[a]	5-15	2.4-3
Linear move	0.51-2.54	0.02-0.06	10-41	16-130	Rectangular	5-15	2.4-3

a. Travelers are available to allow irrigation of any shape field.

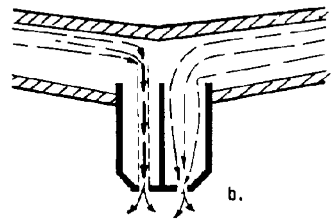
Solid set sprinkler systems for forest crops have some special design requirements. Spacing of sprinkler heads must be closer and operating pressures lower in forests than other vegetation systems because of the interference from tree trunks and leaves and possible damage to bark. An 18 m (60 ft) spacing between sprinklers and a 24 m (80 ft) spacing between laterals has proven to be an acceptable spacing for forested areas [39]. This spacing, with sprinkler overlap, provides good wastewater distribution at a reasonable cost. Operating pressures at the nozzle should not exceed 38 N/cm^2 (55 lb/in^2), although pressures up to 59 N/cm^2 (85 lb/in^2) may be used with mature or thickbarked hardwood species. The sprinkler risers should be high enough to raise the sprinkler above most of the understory vegetation, but generally not exceeding 1.5 m (5 ft). Low-trajectory sprinklers should be used so that water is not thrown into the tree canopies, particularly in the winter when ice buildup on pines and other evergreen trees can cause the trees to be broken or uprooted.

A number of different methods of applying wastewater during subfreezing temperatures in the winter have been attempted. These range from various modifications of rotating and nonrotating sprinklers to furrow and subterranean applications. General practice is to use lowtrajectory, single nozzle impact-type sprinklers, or low trajectory, double nozzle hydraulic driven sprinklers. A spray nozzle used at West Dover, Vermont, is shown in Figure 4-5.

Installation of a buried solid-set irrigation system in existing forests must be done with care to avoid excessive damage to the trees or soil. Alternatively, solid-set systems can be placed on the surface if adequate line drainage is provided (see Figure 4-6). For buried systems, sufficient vegetation must be removed during construction to ensure ease of installation while minimizing site disturbance so that site productivity is not decreased or erosion hazard increased. A 3 m wide (10 ft) path cleared for each lateral meets these objectives. Following construction, the disturbed area must be mulched or seeded to restore infiltration and prevent erosion. During operation of the land treatment system, a 1.5 m 9 ft) radius should be kept clear around each sprinkler. This practice allows better distribution and more convenient observation of sprinkler operation. Spray distribution patterns will still not meet agricultural standards, but this is not as important in forests because the roots are quite extensive.

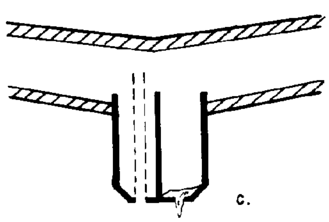


a. SPRAYING



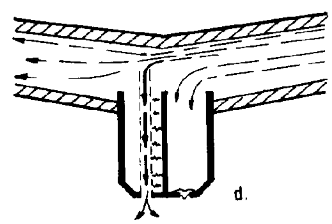
b. DRAINING

BRASS TUBE IN LEFT HALF DRAINS QUICKLY, UNTIL LIQUID LEVEL IS BELOW ITS TOP. THEN ONLY RIGHT HALF CONTINUES TO DRAIN.



c. LINE DRAINED

SMALL AMOUNT OF ICE HAS FORMED TO BLOCK RIGHT HALF OF NOZZLE. BRASS TUBE LEFT HALF IS OPEN AND READY FOR NEXT SPRAY CYCLE.



d. NEXT SPRAY CYCLE

WATER INITIALLY SPRAYS THROUGH THE BRASS TUBE ON THE LEFT SIDE. THE HEAT FROM THE LIQUID MELTS THE ICE PLUG BLOCKING THE RIGHT HALF OF THE NOZZLE AND SPRAYING RESUMES IN THE NORMAL MANNER AS SHOWN IN a.

FIGURE 4-5
FAN NOZZLE USED FOR SPRAY APPLICATION AT WEST DOVER, VERMONT

FIGURE 4-6
SOLID SET SPRINKLERS WITH
SURFACE PIPE IN A FOREST SYSTEM

4.7.3 Service Life of Distribution System Components

The expected service life of the distribution system components is a design consideration and must be used to develop detailed cost comparison. The suggested service lives of common distribution system components are listed in Table 4-24.

4.8 Drainage and Runoff Control

Provisions to improve or control subsurface drainage are sometimes necessary with SR systems to remove excess water from the root zone or to remove salts from the root zone when these conditions adversely affect crop growth. Control of surface runoff is necessary for SR systems using surface distribution methods. In humid areas with intense rain—falls, control of surface drainage is necessary to prevent erosion and may be helpful in reducing the amount of water entering the soil profile and thereby reducing or eliminating the need for subsurface drainage. Design considerations for drainage and runoff control provisions are discussed in the following sections.

4.8.1 Subsurface Drainage Systems

Subsurface drainage systems are used in situations where the natural rate of subsurface drainage is restricted by relatively impermeable layers in the soil profile near the surface or by high ground water. As a result of the restrictive layer, shallow ground water tables can form that extend into the root zone and even to the soil surface.

The major consideration for wastewater treatment is the maintenance of an aerobic zone in the upper soil profile. Many of the wastewater removal mechanisms require an aerobic environment to function most effectively. A travel distance of 0.6 to 1 m (2 to 3 ft) through aerobic soil is considered the minimum distance to achieve treatment by the SR process. Therefore, a water table depth of 1 m (3 ft) or more is desirable from a wastewater treatment standpoint.

TABLE 4-24
SUGGESTED SERVICE LIFE FOR COMPONENTS OF DISTRIBUTION SYSTEM [40]

	Service life[a]	
	Hours[b]	years
Well and casing	--	20
Pump plant housing	--	20
Pump, turbine		
Bowl (about 50% of cost of pump unit)	16,000	8
Column, etc.	32,000	16
Pump, centrifugal	32,000	16
Power transmission		
Gear head	30,000	15
V-belt	6,000	3
Flat belt, rubber and fabric	10,000	5
Flat belt, leather	20,000	10
Power units		
Electric motor	50,000	25
Diesel engine	28,000	14
Gasoline or distillate		
Air cooled	8,000	4
Water cooled	18,000	9
Propane engine	28,000	14
Open farm ditches (permanent)	--	20
Concrete structures	--	20
Concrete pipe systems	--	20
Wood flumes	--	8
Pipe, surface, gated	--	10
Pipe, water works class	--	40
Pipe, steel, coated, underground	--	20
Pipe, aluminum, sprinkler use	--	15
Pipe, steel, coated, surface use only	--	10
Pipe, steel galvanized, surface only	--	15
Pipe, wood buried	--	20
Sprinkler heads	--	8
Solid set sprinkler system	--	20
Center pivot sprinkler system	--	10-14
Side roll traveling system	--	15-20
Traveling gun sprinkler system	--	10
Traveling gun hose system	--	4
Land grading[c]	--	None
Reservoirs[d]	--	None

a. Certain irrigation equipment may have a shorter life when used in a wastewater treatment system.

b. These hours may be used for year-round operation. The comparable period in years was based on a seasonal use of 2,000 h/yr.

c. Some sources depreciate land leveling in 7 to 15 years. However, if proper annual maintenance is practiced, figure only interest on the leveling costs. Use interest on capital invested in water right purchase.

d. Except where silting from watershed above will fill reservoir in an estimated period of years.

For SR systems where wastewater treatment and maximum hydraulic loading rate are the design objectives, the presence of excess moisture in the root zone is of limited concern for crops because water tolerant crops are generally selected for such systems. However, restrictive subsurface layers and resulting high water tables limit the allowable percolation rate and, therefore, the design hydraulic loading rate. Subsurface drains placed above the restrictive layer eliminate the effect of that layer on percolation and allow the design percolation rate to be based on more permeable overlying soil horizons. The design hydraulic loading rate is thereby increased.

In arid regions, the additional problem of salinity control is encountered. With such systems, excess water is applied to remove salts that concentrate in the root zone (Section 4.3.2.3). Where the natural drainage rate is insufficient to remove salty leaching water from the root zone within 2 to 3 days, crop damage due to salinity may occur depending on the tolerance of the crop and the salinity of the applied water (see Section 4.3.2.5). In such cases, the objectives of a subsurface drainage system are to (1) prevent the persistence of high water tables when leaching is practiced, and (2) to keep the water table sufficiently low between growing seasons to minimize evaporation from the water table and resulting salt accumulation in the root zone. As a rule of thumb, the water table should not be permitted to come closer than about 125 cm (49 in.) from the surface to prevent salt accumulation. This minimum depth is greater than those generally used in humid areas. Any drainage water from crop revenue systems that is discharged to surface waters must meet applicable discharge requirements.

The decision to use subsurface drains must be based on the economic benefit to be gained from their use. For example, the cost of installing and maintaining a subsurface drain system should be compared to the value of developing an otherwise unsuitable site or to the cost of a larger land area that will be required if subsurface drains are not used.

Buried plastic, concrete, and clay tile lines are normally used for underdrains. The choice usually depends on price and availability of materials. Where sulfates are present in the ground water, it is necessary to use a sulfate-resistant cement, if concrete pipe is chosen, to prevent excess internal stress from crystal formation. Most tile drains are mechanically laid in a machine dug trench or by direct plowing. Open trenches can be used for subsurface drainage, but if closely spaced, they can interfere with farming operations and consume usable land.

Underdrains are normally buried 1.8 to 2.4 m (6 to 8 ft) deep but can be as deep as 3 m (10 ft) or as shallow as 1 m (3 ft). Drains are normally 10 to 15 cm (4 to 6 in.) in diameter. Spacings as small as 15 to 30 m (50 to 100 ft) may be required for clayey soils. For sandy soils, 120 m (400 ft) is typical with the range being from 60 to 300 m (200 to 1,000 ft).

Procedures for determining the proper depth and spacing of drain lines to maintain the water table below a minimum depth are discussed in Section 5.7. Additional detailed design procedures and engineering aspects of subsurface drainage systems are described in references [41, 42, 43].

4.8.2 Surface Drainage and Runoff Control

Drainage and control of surface runoff is a design consideration for SR systems as it relates to tailwater from surface distribution systems and stormwater runoff from all systems.

4.8.2.1 Tailwater Return Systems

Most surface distribution systems will produce some runoff, which is referred to as tailwater. When partially treated wastewater is applied, tailwater must be contained within the treatment site and reapplied. Thus a tailwater return system is an integral part of an SR system using surface distribution methods. A typical tailwater return system consists of a sump or reservoir, a pump(s), and return pipeline.

The simplest and most flexible type of system is a storage reservoir system in which all or a portion of the tailwater flow from a given application is stored and either transferred to a main reservoir for later reapplication or reapplied from the tailwater reservoir to other portions of the field. Tailwater return systems should be designed to distribute collected water to all parts of the field, not consistently to the same area. If all the tailwater is stored, pumping can be continuous and can commence at the convenience of the operator. Pumps can be any convenient size, but a minimum capacity of 25% of the distribution system capacity is recommended [44]. If a portion of the tailwater flow is stored, the reservoir capacity can be reduced but pumping must begin during tailwater collection.

Cycling pump systems and continuous pumping systems can be designed to minimize the storage volume requirements, but these systems are much less flexible than storage systems. The designer is directed to reference [44] for design procedures.

The principal design variables for tailwater return systems are the volume of tailwater and the duration of tailwater flow. The expected values of these parameters for a well-operated system depend on the infiltration rate of the soil. Guidelines for estimating tailwater volume, the duration of tailwater flow, and suggested maximum design tailwater volume are presented in Table 4-25.

TABLE 4-25
RECOMMENDED DESIGN FACTORS
FOR TAILWATER RETURN SYSTEMS [44]

Permeability					
Class	Rate, cm/h	Texture range	Maximum duration of tailwater flow, % of application time	Estimated tailwater volume, % of application volume	Suggested maximum design tailwater volume, % of application volume
Very slow to slow	0.15-0.5	Clay to clay loam	33	15	30
Slow to moderate	0.5-1.5	Clay loam to silt loam	33	25	50
Moderate to moderately rapid	1.5-15	Silt loams to sandy loams	75	35	70

Runoff of applied wastewater from sites with sprinkler distribution systems should not occur because the design application rate of the sprinkler system is less than the infiltration rate of the soil—vegetation surface. However, some runoff from systems on steep (10 to 30%) hillsides should be anticipated. In these cases, runoff can be temporarily stored behind small check dams located in natural drainage courses. The stored runoff can be reapplied with portable sprinkling equipment.

4.8.2.2 Stormwater Runoff Provisions

For SR systems, control of stormwater runoff to prevent erosion is necessary. Terracing of steep slopes is a well known agricultural practice to prevent excessive erosion. Sediment control basins and other nonstructural control measures, such as contour plowing, no-till farming, grass border strips, and stream buffer zones can be used. Since wastewater application will usually be stopped during storm runoff conditions, recirculation of storm runoff for further treatment is usually unnecessary. Channels or waterways that carry stormwater runoff to discharge points should be designed with a capacity to carry runoff from a storm of a specified return frequency (10 year minimum).

4.9 System Management

4.9.1 Soil Management

Management of the soil involves tillage operations and maintenance of the proper soil chemical properties including plant nutrient levels, pH, sodium levels, and salinity levels. Much of what is discussed under soil management refers to agricultural crop systems, since most forest crop systems require very little soil management.

4.9.1.1 Tillage Operations

One of the principal objectives of tillage operations is to maintain or enhance the infiltration capacity of the soil surface and the permeability of the entire soil profile. In general, tillage operations that expose bare soil should be kept to a minimum. Minimum tillage and no–till methods conserve fuel, reduce labor costs, and minimize compaction of soils by heavy equipment. Conventional plowing (20 to 25 cm or 8 to 10 in.) and preparation of a seedbed free of weeds and trash are necessary for most vegetables and root crops. Many field crops, however, can be planted directly in sod or residues from a previous crop or after partial incorporation of residues by shallow disking. Crop residues left on the surface or partially incorporated to a depth of 8 or 10 cm (3 or 4 in.) provide protection against runoff and erosion during intervals between crops. The decomposition of residues on or near the soil surface helps to maintain a friable, open condition conducive to good aeration and rapid infiltration of water. Actively decomposing organic matter also helps to reduce the concentration of other soluble pollutants and can hasten the conversion of toxic organics, like pesticides, to less toxic products.

At sites where clay pans have formed and reduce the effective permeability of the soil profile, it may be necessary to plow very deeply (60 to 180 cm or 2 to 6 ft) to mix impermeable subsoil strata with more permeable surface materials. Impermeable pans formed by vehicular traffic (plow pans) or by cementation of fine particles (hard pans) can be broken up by subsoiling equipment that leaves the surface protected by vegetation or stubble. To be effective, however, the subsoiling equipment must completely break through the pan layers. This is difficult if the pan layers are more than 30 cm (1 ft) thick. Local soil conservation district personnel should be consulted regarding tillage practices appropriate for specific crops, soils, and terrain.

4.9.1.2 Nutrient Status

During design, it is recommended that the nutrient status of the soil be evaluated. Periodic evaluation is recommended as part of the system monitoring program (Section 4.10).

Sufficient nitrogen, phosphorus, and most other essential nutrients for plant growth are generally supplied by most wastewaters. Potassium is the nutrient most likely to be deficient since it is usually present in low concentrations in wastewater. For soils having low levels of natural potassium, the following relationship has been developed to estimate potassium fertilizer requirements:

$$K_f = 0.9U - K_{ww} \qquad (4\text{-}13)$$

where K_f = annual fertilizer potassium needed, kg/ha

U = estimated annual crop uptake of nitrogen, kg/ha

K_{ww} = amount of potassium applied in wastewater, kg/ha

On the basis of commonly used test methods for available nutrients, the University of California Agricultural Extension Service has developed a summary of adequate available levels in the soil of the nutrients most commonly deficient for some selected crops. This summary is presented in Table 4-26. Critical values for nitrogen are not included because there are no well accepted methods for determining available nitrogen.

Table 4-26
APPROXIMATE CRITICAL LEVELS OF NUTRIENTS IN SOILS FOR SELECTED CROPS IN CALIFORNIA

Nutrient	Approximate critical range, ppm	Test method
Phosphorus		0.5 M $NaHCO_3$ extraction at pH 8.5
Range and pasture	10	
Field crops and warm season vegetables	5-9	
Cool season vegetables	12-20	
Potassium		1.0 N ammonium acetate extraction at pH 7.0
Grain and alfalfa	45-55	
Cotton	55-65	
Potatoes	90-110	
Zinc	0.4-0.6	DPTA extraction

4.9.1.3 Soil pH Adjustment

In general, a pH less than 4.2 is too acid for most crops and above 8.4 is too alkaline for most crops. The optimum pH range for crop growth depends on the type of crop. Extremes in the soil pH also can affect the performance of an SR system or indicate problem conditions. Below pH 6.5, the capacity of the soil to retain metal is reduced. A soil pH above 8.5 generally indicates a high sodium content and possible permeability problems.

The pH of soils can be adjusted by the addition of liming materials or acidulating chemicals. A pH adjustment program should be based on the recommendations of a professional agricultural consultant or county or state farm adviser.

4.9.1.4 Exchangeable Sodium Control

Soils containing excessive exchangeable sodium are termed "sodic" soils. A soil is considered sodic when the percentage of the total cation exchange capacity (CEC) occupied by sodium, the exchangeable sodium percentage (ESP), exceeds 15%. High levels of sodium cause low soil permeability, poor soil aeration, and difficulty in seedling emergence. Fine-textured soil may be affected at an ESP above 10%, but coarse-textured soil may not be damaged until the ESP reaches about 20%. The ESP should be determined by laboratory analysis before design if sodic soils are known to exist in the area of the site. Sodic soil conditions may be corrected by adding soluble calcium to the soil to displace the sodium on the exchange and removing the displaced sodium by leaching. Advice on correcting sodic soils should be obtained from agricultural consultants or farm advisers.

4.9.1.5 Salinity Control

Salinity control may be necessary in arid climates where natural rainfall is insufficient to flush salts from the root zone. The salinity level of a soil is usually measured on the basis of the electrical conductivity of an extract solution from a saturated soil (EC_e). Saline soils are defined as those yielding an EC_e value greater than 4,000 micromhos/cm at 25 °C (77 °F).

Soils that are initially saline may be reclaimed by leaching; however, management of the leachate is often required to protect ground water quality. The U.S. Department of Agriculture*s <u>Handbook 60</u> [45] deals with the diagnosis and improvement of such soils for agricultural purposes. This reference can be used as a practical guide for managing saline and saline-sodic soil conditions in arid and semiarid regions.

4.9.2 Crop Management

Because of their substantially different requirements, the management of agricultural crops and forest crops are discussed separately.

4.9.2.1 Agricultural Crop Planting and Harvesting

Local extension services or similar experts should be consulted regarding planting techniques and schedules. Most crops require a period of dry weather before harvest to mature and reach a moisture content compatible with harvesting equipment. Soil moisture at harvest time should be low enough to minimize compaction by harvesting equipment. For these reasons, application should be discontinued well in advance of harvest. The time required for drying will depend on the soil drainage and the weather. A drying time of 1 to 2 weeks is usually sufficient if there is no precipitation. However, advice on this should be obtained from local agricultural experts.

Harvesting of grass crops and alfalfa involves regular cuttings, and a decision regarding the trade-off between yield and quality must be made. Advice can be obtained from local agricultural experts. In the northeast and north central states, three cuttings per season have been successful with grass crops.

4.9.2.2 Grazing

Grazing of pasture by beef cattle or sheep can provide an economic return for SR systems. No health hazard has been associated with the sale of the animals for human consumption.

Grazing animals return nutrients to the ground in their waste products. The chemical state (organic and ammonia nitrogen) and rate of release of the nitrogen reduces the threat of nitrate pollution of the ground water. Much of the ammonia–nitrogen volatilizes and the organic nitrogen is held in the soil where it is slowly mineralized to ammonium and nitrate forms. Steer and sheep manure contain approximately 20% nitrogen after volatile losses, of which about 40% is mineralized in the first year, 25% in the second, and 6% in successive years [41].

In terms of pasture management, cattle or sheep must not be allowed on wet fields to avoid severe soil compaction and reduced soil infiltration rates. Wet grazing conditions can also lead to animal hoof diseases. Pasture rotation should be practiced so that wastewater can be applied immediately after the livestock are removed. In general, a pasture area should not be grazed longer than 7 days. Typical regrowth periods between grazings range from 14 to 35 days. Depending on the period of regrowth provided, one to three water applications can be made during the regrowth period. Rotation grazing cycles for 3 to 8 pasture areas are given in Table 4-27. At least 3 to 4 days drying time following an application should be allowed before livestock are returned to the pasture.

Table 4-27
GRAZING ROTATION CYCLES FOR
DIFFERENT NUMBERS OF PASTURE AREAS

No. of pasture areas	Rotation cycle, days	Regrowth period, days	Grazing period, days
3	21	14	7
4	28	21	7
5	35	28	7
6	36	30	6
7	35	28	7
8	32	28	4

4.9.2.3 Agricultural Pest Control

Problems with weeds, insects, and plant diseases are aggravated under conditions of frequent water application, particularly when a single crop is grown year after year or when no-till practices are used. Most pests can be controlled by selecting resistant or tolerant crop varieties and by using pesticides in combination with appropriate cultural practices. State and local experts should be consulted in developing an overall pest control program for a given situation.

4.9.2.4 Forest Crops

The type of forest crop management practice selected is determined by the species mix grown, the age and structure of the stand, the method of reproduction best suited and/or desired for the favored species, terrain, and type of equipment and technique used by local harvesters. The most typical forest management situations encountered in land treatment are management of existing forest stands, reforestation, and short-term rotation.

Existing Forest Ecosystems

The general objective of the forest management program is to maximize biomass production. The compromise between fully attaining a forest*s growth potential and the need to operate equipment efficiently (distribution and harvesting equipment) requires fewer trees per unit area. These operations will assure maintenance of a high nutrient uptake, particularly nitrogen, by the forest.

For uneven—aged forests, the desired forest composition, structure, and vigor can be best achieved through thinning and selective harvest. However, excessive thinning can make trees susceptible to wind throw and caution is advised in windy areas. The objective of these operations would be to maintain an age class distribution in accordance with the concept of optimum nutrient storage (see Section 4.3). The maintenance of fewer trees than normal would permit adequate sunlight to reach the understory to promote reproduction and growth of the understory. Thinning should be done initially prior to construction of the distribution system and only once every 10 years or so to minimize soil and site damage.

In even-aged forests, trees will all reach harvest age at the same time. The usual practice is to clear-cut these forests at harvest age and regenerate a stand by either planting seedlings, natural seeding, sprouting from stumps (called coppice), or a combination of several of the methods. Even-aged stands may require a thinning at an intermediate age to maintain maximum biomass production. Coniferous forests, in general, must be replanted, whereas hardwood forests can be reproduced by coppice or natural seeding.

The concept of “whole-tree harvesting” should be considered for all harvesting operations, whether it be thinning, selection harvest, or clear-cut harvest. Whole-tree harvesting removes the entire standing tree: stem, branches, and leaves. Thus, 100% of the nitrogen accumulated in the aboveground biomass would be removed (see Section 4.3.2.1).

Prescribed fire is a common management practice in many forests to reduce the debris or slash left on the site during conventional harvesting methods. During the operation, a portion of the forest floor is burned and nitrogen is volatilized. Although this represents an immediate benefit in terms of nitrogen removal from the site, the buffering capacity that the forest floor offers is reduced and the likelihood of a nitrate leaching to the ground water is increased when application of wastewater is resumed.

Reforestation

Wastewater nutrients often stimulate the growth of the herbaceous vegetation to such an extent that they compete with and shade out the desirable forest species. Herbaceous vegetation is necessary to act as a nitrogen sink while the trees are becoming established, and therefore, cultural practices must be designed to control but not eliminate the herbaceous vegetation. As the tree crowns begin to close, the herbaceous vegetation will be shaded and its role in the renovation cycle reduced. Another alternative to control of the herbaceous vegetation is to eliminate it completely and reduce the hydraulic and nutrient loading during the establishment period.

Short-Term Rotation

Short–term rotation forests are plantations of closely spaced hardwood trees that are harvested repeatedly on cycles of less than 10 years. The key to rapid growth rates and biomass development is the rootstock that remains in the soil after harvest and then resprouts. Short-term rotation harvesting systems are readily mechanized because the crop is uniform and relatively small.

Using conventional tree spacings of 2.5 to 4 m (8 to 12 ft), research on systems where wastewater has been applied to short–term rotation plantations has shown that high growth rates and high nitrogen removal are possible [16]. Planted stock will produce only 50% to 70% of the biomass produced following cutting and resprouting [47, 48]. If nitrogen and other nutrient uptake is proportional to biomass, the first rotation from planted stock will not remove as much as subsequent rotations from coppice. Therefore, the initial rotation must receive a reduced nutrient load or other herbaceous vegetation must be employed for nutrient storage. Alternatively, closer tree spacings may be used to achieve desired nutrient uptake rates during initial rotation.

4.10 System Monitoring

The broad objectives of a monitoring program for an SR system are to determine if the effluent quality requirements are being met, to determine if any corrective action is necessary to protect the environment or maintain the renovative capacity of the system, and to aid in system operation. The components of the environment that need to be observed include water quality, the soils receiving wastewater, and in some cases, vegetation growing in soils that are receiving wastewater.

4.10.1 Water Quality Monitoring

Monitoring of water quality for land application systems can be more complex than for conventional treatment systems because nonpoint discharges of system effluent are involved. Monitoring of applied wastewater and renovated water quality is useful for process control. For SR systems, renovated water would only be monitored in cases where underdrains are used. Monitoring of receiving waters, surface or ground water, may be required by regulatory authorities.

In most cases, a water quality monitoring program, including constituents to be analyzed and frequency of analysis, will be prescribed by local regulatory agencies. It may be desired to monitor additional constituents or parameters for purposes of crop and soil management.

Ground water monitoring data are difficult to interpret unless sampling wells are located properly and correct sampling procedures are followed. In addition to quality, the depth to ground water should be measured at the sampling wells to determine if the hydraulic response of the aquifer is consistent with what was anticipated. For SR systems, a rise in water table levels to the root zone would necessitate corrective action such as reduced hydraulic loading or adding underdrainage. The appearance of seeps or perched ground water tables might also indicate the need for corrective action.

4.10.2 Soils Monitoring

In some cases, application of wastewater to the land will result in changes in soil properties. Results of soil sampling and testing will serve as the basis for deciding whether or not soil properties should be adjusted by the application of chemical amendments. Annual monitoring of the soil properties described in Section 4.9.1 is sufficient for most systems.

It is recommended that the level of trace elements of concern (see Chapter 9) in the soil be monitored every few years so that the rate of accumulation can be observed and toxic levels avoided. Total metal analysis by hot acid digestion is recommended for monitoring and comparison purposes.

4.10.3 Vegetation Monitoring

Plant tissue analysis is more revealing than soil analysis with regard to deficient or toxic levels of elements. If visual symptoms of nutrient deficiencies or toxicities appear, plant tissue testing can be used for confirmation, and corrective action can be taken. A regular plant tissue monitoring program can often detect deficiencies or toxicity before visual symptoms and damage to the plant occurs.

Nitrate should be determined in forages or leafy vegetables if there is reason to suspect concentrations which might be toxic to livestock. Detailed information on plant sampling and testing may be found in references [49, 50]. Extension specialists or local farm advisers should be consulted regarding plant tissue testing.

4.11 Facilities Design Guidance

The purpose of this section is to provide guidance on aspects of facilities design that may be unfamiliar to some environmental engineers.

- Standard surface irrigation practice is to produce longitudinal slopes of 0.1 to 0.2% with transverse slopes not exceeding 0.3%.

  Step 1. Rough grade to 5 cm (0.15 ft) at 30 m (100 ft) grid stations.

  Step 2. Finish grade to ±3 cm (0.10 ft) at 30 m (100 ft) grid stations with no reversals in slope between stations.

  Step 3. Land plane with a 18 m (60 ft) minimum wheel base, land plane to a “near perfect” finished grade.

- Access to sprinklers or distribution piping should be provided every 390 m (1,300 ft) for convenient maintenance.

- Both asbestos-cement and PVC irrigation pipe are rather fragile and require care in handling and installation.

- Diaphragm-operated globe valves are recommended for controlling flow to laterals.

- All electric equipment should be grounded, especially when associated with center pivot systems.

- ! Automatic controls can be electrically, hydraulically, or pneumatically operated. Solenoid actuated, hydraulically operated (by the wastewater) valves with small orifices will clog from the solids.

- ! Valve boxes, 1 m (36 in.) or larger, should be made of corrugated metal, concrete, fiber glass, or pipe material. Valve boxes should extend 15 cm (6 in.) above grade to exclude stormwater.

- ! Low pressure shutoff valves should be used to avoid continuous draining of the lowest sprinkler on the lateral.

- ! Automatic operation can be controlled by timer clocks. It is important that when the timer shuts the system down for any reason that the field valves close automatically and that the sprinkling cycles resume as scheduled when sprinkling commences. The clock should not reset to time zero when an interruption occurs.

- ! High flotation tires are recommended for land treatment system vehicles. Recommended soil contact pressures for center pivot machines are presented in Table 4-28.

TABLE 4-28
RECOMMENDED SOIL CONTACT PRESSURE

% fines	N/cm^2	$lb/in.^2$
20	17	25
40	11	16
50	8	12

Note: To illustrate the use of this table, if 20% of the soil fines pass through a 200-mesh screen, the contact pressure of the supporting structure to the ground should be no more than 17 N/cm^2 (25 $lb/in.^2$). If this is exceeded, one can expect wheel tracking problems to occur.

4.12 References

1. Benham-Blair and Affiliates, Inc. and Engineering Enterprises, Inc. Long-term Effects of Land Application of Domestic Wastewater: Dickinson, North Dakota, Slow Rate Irrigation Site. U.S. Environmental Protection Agency. EPA-600/2-79-144. August 1979.

2. Demirjian, Y.A. et al. Muskegon County Wastewater Management System. U.S. Environmental Protection Agency. EPA-905/2-80-004. February 1980.

3. Hossner, L.R., et al. Sewage Disposal on Agricultural Soils: Chemical and Microbiological Implications (San Angelo, Texas). U.S. Environmental Protection Agency. EPA-600/2-78-131a,b. June 1978.

4. Jenkins, T.F. and A.J. Palazzo. Wastewater Treatment by a Slow Rate Land Treatment System. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory. CRREL Report 81-14. Hanover, New Hampshire. August 1981.

5. Koerner, E.L. and D.A. Haws. Long-Term Effects of Land Application of Domestic Wastewater: Roswell, New Mexico, Slow Rate Irrigation Site. U.S. Environmental Protection Agency. EPA-600/2-79-647. February 1979.

6. Iskandar, I.K., R.P. Murrmann, and D.C. Leggett. Evaluation of Existing Systems for Land Treatment of Wastewater at Manteca, California and Quincy, Washington. U.S. Army Cold Regions Research and Engineering Laboratory. CRREL Report 77-24. September 1977.

7. Nutter, W.L., R.C. Schultz, and G.H. Brister. Land Treatment of Municipal Wastewater on Steep Forest Slopes in the Humid Southeastern United States. Proceedings of Symposium on Land Treatment of Wastewater. Hanover, New Hampshire. August 20-25, 1978.

8. Stone, R. and J. Rowlands. Long-Term Effects of Land Application of Domestic Wastewater: Mesa, Arizona, Irrigation Site. U.S. Environmental Protection Agency. EPA-600/2-80-061. April 1980.

9. Enfield, C.G. and B.E. Bledsoe. Kinetic Model for Orthophosphate Reactions in Mineral Soils. EPA-660/2-75-002. U.S. Government Printing Office. June 1975.

10. Land as a Waste Management Alternative. R.C. Loehr, ed. Ann Arbor Science. Ann Arbor, Michigan. 1977.

11. Overman, A.R. Wastewater Irrigation at Tallahassee, Florida. U.S. Environmental Protection Agency. EPA-600/2-79-151. August 1979.

12. Stone, R. and J. Rowlands. Long-Term Effects of Land Application of Domestic Wastewater: Camarillo, California, Irrigation Site. U.S. Environmental Protection Agency. EPA-600/2-80-080. May 1980.

13. Tofflemire, T.J. and M. Chen. Phosphate Removal by Sands and Soils. In: Land as a Waste Management Alternative. Loehr, R.C. (ed). Ann Arbor, Ann Arbor Science. 1977.

14. Uiga, A. and R.W. Crites. Relative Health Risks of Activated Sludge Treatment and Slow Rate Land Treatment. Journal WPCF, 52(12) :2865-2874. December 1980.

15. Pratt, P.F. Quality Criteria for Trace Elements in Irrigation Waters. University of California, Riverside, Department of Soil Science and Agricultural Engineering. 1972.

16. National Academy of Science. Water Quality Criteria 1972. Ecological Research Series. U.S. Environmental Protection Agency. Report No. R3-73-033. March 1973.

17. U.S. Environmental Protection Agency. Preliminary Survey of Toxic pollutants at the Muskegon Wastewater Management System. Robert S. Kerr Environmental Research Laboratory, Groundwater Research Branch. Ada, Oklahoma. 1977.

18. Hinrichs, D.J. Design of Irrigation Systems for Agricultural Utilization of Effluent. Presented at the California Water pollution Control Association Annual Conference; Monterey, Calif. May 1, 1980.

19. Smith, W.H. and J.O. Evans. Special Opportunities and Problems in Using Forest Soils for Organic Waste Application. In: Soils for Management of Organic Wastes and Waste Waters. ASA, CSSA, SSSA, Madison, Wisconsin. pp. 429-451. 1977.

20. Palazzo, A.J., and J.M. Graham. Seasonal Growth and Uptake of Nutrients by Orchardgrass Irrigated with Wastewater. U.S. Army Cold Regions Research and Engineering Laboratory. CRREL Report 81-8. June 1981.

21. Duscha, L.A. Dual Cropping Procedure for Slow Infiltration of Land Treatment of Municipal Wastewater. Department of the Army, Engineering Technical Letter No. 1110-2-260. March 12, 1981.

22. McKim, H.L., et al. Wastewater Application in Forest Ecosystems. CRREL Report 119, Corps of Engineers, U.S. Army. May 1980.

23. USDA Forest Service. Impact of Intensive Harvesting on Forest Nutrient Cycling. Northeast Forest Experiment Station. Broomall, Pa. 1979.

24. Jensen, M.E. (ed.). Consumptive Use of Water and Irrigation Water Requirements. ASCE. ASCE Committee on Irrigation Water Requirements. 1973.

25. Doorenbos, J. and W.O. Pruitt. Guidelines for Predicting Crop Water Requirements. Irrigation and Drainage Paper 24. Presented at United Nations Food and Agriculture Organization. Rome. 1975.

26. Irrigation Water Requirements. Technical Release No. 21, U.S. Department of Agriculture, Soil Conservation Service. September 1970.

27. Vegetative Water Use in California, 1974. Bulletin No. 113-3, State of California Department of Water Resources. April 1975.

28. Booher, L.J. and G.V. Ferry. Estimated Consumptive Use and Irrigation Requirements of Various Crops. University of California Agricultural Extension Service, Bakersfield, Calif. March 10, 1970.

29. Ayers, R.S. Quality of Water for Irrigation, Jour. of the Irrigation and Drainage Division, ASCE, Vol. 103, No. IR2. June 1977. pp. 135-154.

30. U.S. Environmental Protection Agency. Facilities Planning, 1982. EPA-430/9-81-012. FRD-25. September 1981.

31. Reed, S.C. Treatment/Storage Ponds for Land Application Systems. CRREL Special Report. December 1981.

32. Environmental Protection Agency. Process Design Manual for Wastewater Treatment Ponds (In Preparation).

33. Bowles, D.S., et al. Coliform Decay Rates in Waste Stabilization Ponds, Journal WPCF, 51(l):87-99, January 1979.

34. Sagik, B.P. et al. The Survival of Human Enteric Viruses in Holding Ponds. Contract Report DAMD 17-75-C-5062. U.S. Army Medical Research and Development Command. 1978.

35. Whiting, D.M. Use of Climatic Data in Estimating Storage Days for Soil Treatment Systems. Environmental Protection Agency, Office of Research and Development. EPA-600/2-76-250. November 1976.

36. Whiting, D.M. Use of Climatic Data in Design of Soil Treatment Systems. EPA-660/2-75-018. Environmental Protection Agency, Office of Research and Development. July 1975.

37. U.S. Department of the Interior, Bureau of Reclamation. Design of Small Dams. Second Edition. U.S. Government Printing Office. 1973.

38. Booher, L.J. Surface Irrigation. FAO Agricultural Development Paper No. 95. Food and Agricultural Organization of the United Nations. Rome. 1974.

39. Myers, E.A. Design and Operational Criteria for Forest Irrigation Systems. In: Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land. The Pennsylvania State University Press, University Park, Pa. p. 265-272. 1979.

40. Evaluation of Land Application Systems. U.S. Environmental Protection Agency. EPA-430/9-75-001. March 1975.

41. Luthin, J.N. (ed.). Drainage of Agricultural Lands. Madison, American Society of Agronomy. 1957.

42. Van Schilfgaarde, J, ed. Drainage for Agriculture. American Society of Agronomy, Madison, Wisconsin. 1974.

43. Drainage of Agricultural Land. A Practical Handbook for the Planning, Design, Construction, and Maintenance of Agricultural Drainage Systems. U.S. Department of Agriculture, Soil Conservation Service. October 1972.

44. Hart, W.E. Irrigation System Design, Colorado State University, Department of Agricultural Engineering. Fort Collins, Colorado. November 10, 1975.

45. Richards, L.A. (ed.). Diagnosis and Improvement of Saline and Alkali Soil. Agricultural Handbook 60. U.S. Department of Agriculture. 1954.

46. California Fertilizer Assn. Western Fertilizer Handbook Sixth Ed. The Interstate Printers and Publishers. 1980.

47. Saucier, J.R. Estimation of Biomass Production and Removal. In: Impact of Intensive Harvesting on Forest Nutrient Cycling. College of Environmental Science and Forestry, State University of New York, Syracuse, New York, p. 172-189. 1979.

48. Steinbeck, K. and C.L. Brown. Yield and Utilization of Hardwood Fiber Grown on Short Rotations. Applied Polymer Symposium 28: 393-401. 1976.

49. Walsh, L.M. and J.D. Beaton, (eds.). Soil Testing and Plant Analysis. Madison, Soil Science Society of America. 1973.

50. Melsted, S.W. Soil-Plant Relationships (Some Practical Considerations in Waste Management). In: Proceedings of the Joint Conference on Recycling Municipal Sludges and Effluents on Land, Champaign, University of Illinois. July 1973. pp. 121-128.